Relationship Between Jaw Opening and Phonetic Complexity:
A Cross-Language Study

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ABSTRACT

The current study employs a simultaneous cross-system monitoring technique to examine the impact of jaw opening on articulatory and vocal behaviours. The purpose of the study is to determine whether an increased jaw opening posture can improve speech and voice quality in a variety of phonetic contexts. Participants were 20 healthy non-smoking adults, including 10 New Zealand English (Mean = 36.5 years, SD = 14) and 10 Mandarin (Mean = 27.5 years, SD = 9.3) native speakers, with five females and five males in each group. Participants were asked to say, with and without an exaggerated jaw opening posture, monosyllabic consonant-vowel (CV) couplets which contained a vowel (/i/, /a/, or /u/) and a consonant selected from the phonemes in their native language. Signals recorded with the acoustic, electroglottographic (EGG), and marker-based video tracking devices were analyzed to yield (i) acoustic measures, including consonant length, fundamental frequency (F0), percent jitter (%jitter), percent shimmer (%shimmer), signal-to-noise ratio (SNR), and frequencies of Formants One and Two (F1 and F2), (ii) EGG measures, including open quotient and speed quotient, and (iii) maximum jaw displacement. A series of two-way Analysis of Variances (ANOVAs) and repeated measures ANOVAs were conducted on the experimental measures to determine whether there was an effect of task (normal vs. exaggerated jaw opening), language (English vs. Mandarin), consonant, or tone (Tones 1 to 4, for the Mandarin group only). Results showed that an exaggerated jaw opening posture resulted in an expansion of vowel space (as shown in the F1-F2 plot for vowels /i/, /a/, and /u/), increased F0, and positive changes in phonatory stability, including decreased %jitter and %shimmer and increased SNR. These findings highlighted the importance of jaw manipulation in speech treatment and supported the hypothesis that an open mouth approach was useful for speech and voice enhancement, suggesting

that jaw opening had a universal effect of reducing phonetic complexity. In addition, some changes of the experimental measures were also shown to be a function of language, consonant, and tone.

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Chapter 1. INTRODUCTION

The present study concerns usage of an open-mouth approach in speech and voice treatment. This chapter provides an overview of the rationale behind the investigation, a literature review, an orientation to the research question, and the purpose, importance, aims, and hypotheses of the study.

1.1 Overview

Speech mechanism is a voluntary motor behaviour involving a complex sensorimotor control process for coordinating movement of articulatory, phonatory, and respiratory muscles in space and time (Gracco & Löfqvist, 1994). During speech production, the jaw not only participates in a variety of vocal tract adjustments for oral resonance but also provides the skeletal foundation and support for lip and tongue movements. For individuals with neuromuscular impairments, such as those exhibiting tight jaw muscles due to upper motor neuron diseases, there may be an excessive resistance to the articulatory movement (i.e., spasticity) resulting in an increased number of speech production errors (Freed, 2000).

A jaw opening or open-mouth approach has been found useful for improving the speech intelligibility of dysarthric patients (Swigert, 1997) as well as for eliciting relaxed vocal musculature in treating hyperfunctional voice (Boone and McFarlane, 2000). It remains unclear, however, how increased jaw displacement may impact on the quality of speech and voice. In terms of production, does jaw opening affect tongue and lip movements, vocal fold vibration, or both? Does the jaw opening effect on speech and voice vary by phonetic context, including the place and manner of articulation of the target speech sounds? In terms of perception, how does an increase in jaw opening assist in improving speech intelligibility? Empirical evidences are needed to help determine whether the jaw opening effect on speech and voice is (a) universal or language-specific and (b) context-free or context-sensitive. To enhance the understanding and application of a jaw-related treatment, a cross-language and cross-system normative study was conducted to investigate whether a jaw opening approach may lead to improvement in speech and voice presumably due to an effect of reducing the complexity of speech motor demands.

1.2 Literature Review

This literature review includes a critical review of the theoretical background of phonetic complexity, jaw opening, and related speech treatment and measurement.

1.2.1 Phonetic Complexity

The term "phonetic complexity" is discussed in this section with regard to its definition and related findings in studies of speech acquisition, production, and perception.

1.2.1.1 Definition of Phonetic Complexity

"Complexity" is a concept that can be defined from at least three perspectives: epistemic, ontological, and functional (Rescher, 1998; Gierut, 2007). According to the explanation presented in Gierut (2007), an epistemic perspective delineates "complexity" by the number of descriptors needed to define a system, an ontological perspective by the level of a hierarchical organization of the constituent elements of a system, and a functional perspective by the degrees of freedom in a system with regard to its governing principles. The three different ways of conceptualizing "complexity" may point to different approaches in solving a problem. For example, in dealing with speech problems, as explained by Gierut (2007), treatment may focus, (a) from the epistemic standpoint, on reducing the number of speech errors, (b) from the ontological standpoint, on targeting constituents at a higher order category in a hierarchy to induce generalization, or (c) from the functional standpoint, on highlighting the governing principles of a system. Amongst the three perspectives, the ontological perspective may be the most useful in defining "phonetic complexity" for clinical use because it is in keeping with the way the phonological system of a language has been conventionally organized and allows for a systematic view of the relationship between constituents and their sub-constituents as well as constituents across different systems. During the course of speech assessment or intervention, the ontological perspective of complexity may be adopted in establishing a task sequence from the simplest to the most complex forms (Paul, 2002).

Depending on the scope and area of concern, linguistic complexity can be defined from different aspects, such as the pragmatic, semantic, syntactic, phonological, and phonetic dimensions. "Phonetic complexity" is a general term concerning the organization of a language's sound system (i.e., a phonological system). In a phonological system, the hierarchical constituents of a word can be represented by phonemes, syllables, and suprasegmental features, each of which consists of a sub-hierarchical organisation (Kuiper & Allan, 1996). For example, phonemes, the smallest sound units required to differentiate words, can be grouped into (a) vowels, which are mainly classified by tongue height and advancement and (b) consonants, which are often organized by place and manner of articulation. Place of articulation refers to the point where the narrowest air passage is formed in the oral tract while manner of articulation the way air is released from the oral tract. Table 1 presents an example of this organization scheme, showing all English (21 in total excluding /η/ and semivowels /j/, and /w/) and Mandarin consonants (21 in total excluding /η/) grouped by place (in columns) and manner (in rows) of articulation, with voiced (or unaspirated in Mandarin) consonants placed immediately below their voiceless (or aspirated in Mandarin) counterparts. This organization scheme provides a phonetic-articulatory framework for relating articulatory and phonatory movements to "phonetic complexity", which may be defined based on the timing of speech acquisition.

1.2.1.2 Phonetic Complexity and Speech Acquisition

Children's speech sound acquisition requires motor skills to integrate precise controls of muscles related to speech production while going through stages of physical growth, linguistic experience, and development of cognitive skills (Kuhl, 2000; Sander, 1972; Smith et al., 1995). Speech-like sound productions may occur first in a child's early babbling, which is around 4 to 6 months (Prather et al., 1975; Sander, 1972; Shames & Anderson, 2002). It is generally agreed that infants acquire phonetic information by listening to speakers in their listening environment such as mothers' speech (Kuhl, 2000; Liu et al., 2003), suggesting a language-specific component in speech acquisition.

Despite the difference in language environment, the phonological process of word production has been shown to be a dynamic process progressing from simple consonant-vowel (i.e., immature prototype word production) to complex multi-syllabic word productions (i.e., mature adults-like speech). Sharkey and Folkins (1985) studied the development of speech motor control skills in 15 normal English-speaking children across all ages (4, 7, and 10 year-olds and adults) and found that motor skills progressed through three sequential stages, starting from (a) simple organization of the motor system, followed in order by (b) complex organization of the motor system and (b) reduced variability of all speech articulatory movements. In general, it was agreed that speech sound acquisition by normally developing children followed a developmental pattern, as evidenced by the orderly manner in which children acquired consonants (Prather et al., 1975; Robb & Bleile, 1994) and vowels (Davis & MacNeilage, 1995; Otomo & Stoel-Gammon, 1992; Selby et al., 2000; Stoel-Gammon & Herrington, 1990).

1.2.1.2.1 Consonant Acquisition

In a study of 147 normally developing English-speaking children aged between two and four years, Prather et al. (1975) used 44 selected pictures from the Photo Articulation Test to elicit speech production, assessing acquisition of consonant sounds in the initial and final positions of a word. The criterion for acquisition of a target phoneme was set at the 75 percent correct level. It was found that (a) in terms of manner of articulation, nasals, plosives, and glides were established earlier than fricatives and affricates in the word-initial position, (b) in terms of place of articulation, bilabial sounds were acquired earlier than alveolar and velar sounds, and (c) in terms of voicing, voiceless sounds emerged earlier than voiced ones. Stoel-Gammon (1985) analyzed the early meaningful speech samples obtained from 34 normally developing children at 3-month intervals when they were 15, 18, 21, and 24 months of age and found the same pattern of phonemic acquisition as previously reported (Prather et al., 1975).

In normative studies of the "age of acquisition" of consonants, the reported "age of acquisition" for a phoneme may differ between studies due to the methodological differences in the definition of "acquisition". "Acquisition" can be defined as the "first appearance", "earliest correct articulation in words", "customary production", or "full mastery" of the target sound form (Sander, 1972). The criterion for "acquisition" can be set as the percentage of children reaching a predetermined level of correct production of the sound form in different word positions or contexts. Despite methodological differences, the general order of speech sound acquisition remains relatively similar across studies. For example, according to an analysis of Templin's study (1957) by Sander (1972), when "acquisition" was defined as correct production by at least 75% of children in the initial, middle, and final positions of a word, the earliest consonants acquired were found to be /m, n, η, p, f, h, w/ (age 3 years), followed in order by /j/ (age 3.5 years), /b, d, k, g, r/ (age 4 years), /s, ʧ, ʃ/ (age 4.5), /t, l, v, θ/ (age 6 years), and /ð, z, ʒ, ʤ/ (age 7 years). When the threshold was lowered to "the median age of customary articulation", all ages of acquisition shifted down in years but the sound acquisition sequence remained relatively unchanged except for a downward shift in the order of acquisition found for /b/ (age 2 years), /t/ (age 2.5 years), /l/ (age 3 years), and /z/ (age 3.5 years).

1.2.1.2.2 Vowel Acquisition

The acquisition of vowels in normally developing children has also been shown to exhibit an orderly developmental trend (Bleile, 1989; Stoel-Gammon & Herrington, 1990). Stoel-Gammon and Herrington (1990) studied vowel development in four young children (two normals and two phonologically disordered subjects) aged around four years. Based on the accuracy rate and the general order of acquisition, it was found that vowel acquisition could be grouped into three stages, with the corner vowels (/i, a, u/), mid back (/o/), and central stressed (/ʌ/) acquired in Stage One, vowels /æ, ʊ, ɔ, ə/ in Stage Two, and the front vowels (/ e , ɛ, ɪ/) and rhotic vowels (/ɚ, ɝ/) in the last stage.

The developmental tendency of vowel acquisition for children can be explained from perceptual-acoustic and kinematic perspectives. From the perceptual-acoustic perspective, the corner vowels (/i, a, u/) may be easier to be identified by listeners than other single vowels due to their comparatively longer duration and larger vowel space. Therefore, productions of these corner vowels were more likely to be perceived as accurate (Shriberg & Kent, 2003). From the kinematic perspective, the distinct tongue height and articulatory anchor points within the vocal cavity for the corner vowels (/i, a, u/) may be easier for young children to achieve than the short vowels (/ɐ, ɛ, ɪ/). In a longitudinal study of vowel articulation in four healthy boys at 15, 18, 21 and 36 months of age, Selby et al. (2000) found that vowels with less kinematic requirements tended to be established earlier than those with more complex coordination.

1.2.1.2.3 Delayed Speech Acquisition

Delayed speech acquisition may be caused by an impaired neuromuscular control of the speech mechanism or by a sensory problem such as hearing loss (Odding et al., 2006). Speech acquisition in children with motor speech disorders was characterized by (a) delays in the development of canonical babbling and (b) development of abnormal or compensatory patterns of articulatory movement (Levin, 1999; Pena-Brooks & Hegde, 2000). Levin (1999), in a study of the speech of eight non-epileptic and full-term born one-year-old infants (six males and two females) with cerebral palsy (CP), identified developmental delays in babbling and restricted phonetic repertories as the two major speech-related features of neuromotor disorders. It was found that monosyllabic utterances were the only speech-like patterns shown in infants with CP during the babbling stage. In monosyllabic utterances, low and back vowels were found to be predominant in both normally developing and CP children (Levin, 1999), suggesting that a large jaw displacement with minimal tongue displacement might be associated with the lowest level of motor demand in speech production.

As "phonetic complexity" can be related to compound phonetic gestures, the basic functional units of the speech motor system (Fowler & Saltzman, 1993), relaxing the speech motor demands may be considered a way to reduce phonetic complexity. Consonant clusters and pharyngeal consonants, for example, have been described as phonetically complex because they were considered to be associated with a complicated mechanism for coordinating neuromuscular activities (Elgendy & Pols, 2001; Jakielski, 1998). The smoothness or adequacy of speech production may depend, however, not only on a motor programme controlling articulatory movements but also on a linguistic structure dictating the organisation of the motor programme (Abbeduto, 1985; Smith & Kleeck, 1986). From the linguistic viewpoint, "phonetic complexity" may be gauged based on syntactic complexity (Abbeduto, 1985) or some calculations of phonetic products that may or may not be totally motor-based (Nelson & Bauer, 1991). In a study comparing the speech production of individuals in three age groups, including 5-year-old, 8-year-old, and adult groups, Abbeduto (1985) found that sentences with a more complex linguistic structure led to longer syllable duration in production, suggesting that the size of the motor programme and the number of retrievals required for its execution were not independent of the linguistic structure of an utterance.

1.2.1.3 Phonetic Complexity and Speech Production

Regardless of the source of speech production errors, an examination of the phonetic contexts associated with a higher incidence of inaccurate or incongruent speech patterns, such as those found in consonant clusters and stuttering, may help identify ways to reduce phonetic complexity.

1.2.1.3.1 Observations in Consonant Clusters

Consonant clusters have been found to be one of the last phonetic constructs acquired by children (Kent, 2004; Jakielski, 1998; MacNeilage & Davis, 1990, 1995; Vihman, 1992). Consonant clusters were often found to be misarticulated by individuals with phonological or motor speech disorders (Hodson & Paden, 1983; Pena-Brooks & Hegde, 2000) as well as normally developing individuals and those for whom English is a second language (Bernthal & Bankson, 2004; Jeng, 2000; Jeng et al., 2006; Liu et al., 2000; Pena-Brooks & Hegde, 2000; Platt et al., 1980). As an increase in the complexity of the initial sounds in a word or syllable may lead to longer vocal latency, it appears that the number of sequential decisions and executions required to activate and organise phonologic structures prior to speech production would incur a higher demand on the retrieval process and motor planning. Reduction or substitution of sounds in a cluster may result from a phonological process serving to lower the complexity of articulatory gestures.

1.2.1.3.2 Observations in Stuttering

Phonetic complexity has been shown in recent studies to have an effect on the stuttering rate for individuals with stuttering (Dworzynski & Howell, 2004; Howell et al., 2006; Howell & Au-Yeung, 2007). It is generally agreed that stuttering events do not occur in utterances randomly (Dworzynski & Howell, 2004). While it remains a controversial issue as to how linguistic characteristics may be related to stuttering events, phonetic complexity has been considered a universal variable affecting stuttering rate across languages (Dworzynski & Howell, 2004; Howell et al., 2006; Howell & Au-Yeung, 2007).

Dworzynski and Howell (2004) used an index of phonetic complexity (IPC) proposed by Jakielski (1998) to examine the effect of phonetic complexity on stuttering rate in 50 monolingual German-speaking and 26 monolingual English-speaking children and adults. Stuttering rate was found to increase as the IPC score of content words increased in stuttering participants over six years old. Words most frequently stuttered were found in stuttering children to be those containing multi-syllables, dorsal consonants, fricatives, affricates, liquids, consonants at word-ending position, or variegated consonants. Similarly, adult stutterers were found to stutter more on long words and words with dorsal consonants, fricatives, affricates, liquids, consonants at word-ending position, consonant clusters, and heterorganic consonants. It appears that both word length and consonant context have an impact on stuttering rate irrespective to age and language.

In contrast, studies on the early stage of stuttering in young children revealed that function words, including prepositions, articles, and many monosyllabic words, are most likely to be stuttered rather than words with higher phonetic complexity (Bloodstein & Grossman, 1981). For example, in a study of 24 pre-school stuttering children (9 females and 15 males, aged between 29 to 59 months), Throneburg et al. (1994) investigated the relationship between stuttering and phonetic complexity using three different ways of grouping, including (i) 12 developmentally late emerging acquired consonants (/r, l, s, z, ʤ, v, ʧ, h, θ, ð, ʃ, ʒ/) (Prather et al., 1975; Sander, 1972), (ii) consonant strings/consonant cluster, and (iii) multiple syllables. None of these three phonetic factors were found to have an effect on the stuttering rate in the pre-school children included in that study, suggesting that the effect of phonological complexity on stuttering may be affected by other factors.

1.2.1.4 Phonetic Complexity and Speech Treatment

Despite limited direct evidences relating phonetic factors to the ease of speech production, phonetic complexity is often referred to in speech assessment and treatment (Gierut, 2007; Jakielski, 1998; MacNeilage & Davis, 1990, 1995; Nelson & Bauer, 1991; Strand & McCauley, 1999). In the selection of assessment or training materials, it is often assumed that speech production difficulty is increased as the length and phonetic complexity of the utterance increases (Strand & McCauley, 1999).

The concept of “phonetic complexity” has been applied in both assessment and intervention for individuals with phonological (Bernthal & Bankson, 2004) or motor speech disorders (Duffy, 2005). In managing motor speech disorders, for example, phonetic complexity is taken into consideration when ordering the training sequence for articulation therapy and motor oriented drills, progressing from isolated consonants to syllables, words, phrases, sentences and so forth. These organised activities which involve some form of biofeedback are thought to be most effective to establish a novel behaviour underlying motor learning principles and stages (Paul, 2002; Yorkston et al., 1999).

1.2.1.5 Summary

No consensus on the definition of phonetic complexity was found in the literature. Phonetic complexity can be defined based on a normative developmental scale (from the developmental perspective), a combination of phonetic gestures (kinematic perspective), a higher order of linguistic structure, which determines the unit size for sensorimotor programming (linguistic perspective), or other cognitive skills. Some models of classifying phonetic complexity have been found useful for comparing and interpreting speech error behaviours. The common application of a hierarchical approach in speech treatment suggests that certain manipulation of vocal and articulatory movements may be considered productive in reducing phonetic complexity.

1.2.2 Jaw Opening

The jaw plays an important role in speech articulation, with its structural support to the tongue and lips and its movement found to be more remarkable in speech articulation than the upper and lower lip movement for both adults and children (Green et al., 2000). Most importantly, the jaw is considered a predominant articulator contributing to the development of speech production at the early stage (Green et al., 2000; Green et al., 2002; MacNeilage & Davis, 1990).

This section reviews studies of "jaw opening" in speech acquisition as well as in normal and abnormal speech production and examines the application of "jaw opening" in the management of speech motor and voice disorders. The term "jaw opening" encompasses meanings such as "jaw position at maximum jaw lowering", "maximum vertical value", "jaw displacement", or "open mouth" (Boone & McFarlane, 2000; Erickson, 1998). In speech and voice treatment, "jaw opening" is implicated by (a) the "hyperarticulation" or "overarticulation" technique commonly used to improve articulatory precision and thus speech intelligibility (Freed, 2000) and (b) the "open mouth", "yawn-sigh", and "chewing" techniques, which aim at dropping and relaxing the jaw to alleviate signs of vocal hyperfunction (Cookman & Verdolini, 1999).

1.2.2.1 Jaw Opening in Speech Acquisition

The jaw has been shown to be the prime mover for speech articulation in children between ages one and six years old (Green et al., 2000). As compared with speech of young adults, children's lip and jaw coordination was found to undergo great changes in the early years and continue to be modified past age six (Green et al., 2000). Green et al. (2000), based on the finding that articulatory control significantly influenced the pattern of speech sound acquisition and exhibited a sequential developmental trend, concluded that early jaw movement patterns were most relevant to the development of the oral motor control skills needed to acquire more and further refined articulations (Green et al., 2000).

1.2.2.1.1 Frame and Content Theory

According to the frame/content theory of speech evolution, mandibular-driven vocal tract oscillations provide the foundation of motor patterns for early acquisition of the speech motor skills that require integration of the lower lips and the tongue (MacNeilage & Davis, 1990, 2005; MacNeilage, 1998). MacNeilage and Davis (1990, 1995) proposed that during early speech, the regularity of rhythmic mandibular oscillation of the mouth in infants resulted in a spatio-temporal timing pattern that can be perceived as syllable-like. A universal syllable type used across languages is referred to as the "frame" while the rhythmic syllable-like mandibular pattern exhibited by the infants as "content". Within the "frame", changes in the amplitudes of mandibular cycles may trigger a series of changes of vowel and consonant-like utterances leading to variegated patterns of simple frame-related CV syllables and a variety of CV sequences in babbling (MacNeilage & Davies, 2000; Davies et al., 2002). Based on this theory, the dynamic kinematic adjustments of jaw movement play a significant role in accounting for the complex acquisition and evolution of speech production in infants.

1.2.2.1.2 Jaw Opening and Phonetic Complexity

The origin of word formation in children has been recognized as a consonant-vowel (CV) sequence, including labial consonant followed by vowel and later coronal sound followed by vowel (MacNeilage & Davis, 2000). Three intrasyllabic CV sequences, including labial consonant followed by central vowel, coronal consonant followed by front vowel, and dorsal consonant followed by back vowel, were frequently found in infant's babbling and first words (MacNeilage & Davis, 2000). Babbling has been found to be an essential activity for speech development (Bleile, Stark, & McGowan, 1993). The tendency for consonants to be coupled with vowels requiring the least amount of changes in tongue or jaw placement in early speech or speech-like productions suggests the placement of the jaw as well as the tongue, which is the common denominator between consonants and vowels in sound formation, may play a key role in determining the difficulty of speech motor control and thus the pattern for speech development. Most researchers appear to agree that infants start out moving the jaw, the most stable articulator, to utter sounds and progress to superimpose tongue movement control along with a more complex interaction between the vocal apparatus and cognition to the point where a complex adult speech model is assimilated (Green et al., 2002; MacNeilage & Davis, 2000; Stoel-Gammon, 1985).

1.2.2.1.3 Jaw Opening and Voice Contrast

Although changes in speech motor control during early speech acquisition may be affected by the simultaneous development of language skills throughout the childhood (Grigos et al., 2005), the importance of mandibular control in speech articulation is most evident considering its impact on articulatory and laryngeal movement during speech development. During early speech development, the acquisition of the voicing contrast is most closely associated with changes in the jaw kinematics for oral opening, in comparison with that for the lip displacement, which contributes to a more precise speech motor control between laryngeal and oral structures (Gracco & Löfqvist, 1994). This is because children may use the most stable articulator, the jaw, rather than the lips to facilitate linguistic changes (Green et al., 2002; Grigos et al., 2005). For example, in a longitudinal study of the development of the speech motor control of lip and jaw movements during acquisition of the phonemic contrast for bilabial stops, Grigos et al. (2005) concluded through observations on six children (4 females and 2 males, aged from 19 to 21 months) and

10 adults (all females, aged from 20 to 35 years) that the jaw was more active than the lip in the production of different sounds, as reflected in the increased displacement and velocity and a more precise timing control of articulatory and laryngeal movements in oral opening rather than in oral closing. Therefore, the kinematic changes in jaw velocity and displacement appear to play a key role in accommodating the oral articulatory gestures to acquire the voice contrast.

1.2.2.2 Jaw Opening in Motor Speech Disorders

Individuals with motor speech disorders may present difficulties in the neuromuscular control for sequencing speech. It has been shown that up to 80 percent of individuals with CP have at least some speech impairment, such as dysarthria (Levin, 1999; Odding et al., 2006), exhibiting more errors in producing speech sounds which require more complicated neuromuscular control of laryngeal, velopharyngeal, and articulatory movements. Dysarthric speech has also been shown to exhibit smaller vowel space areas as well as reduced vowel and word intelligibilities (Ansel & Kent, 1992; Jeng, 2000; Jeng et al., 2006; Liss et al., 2000; Liu et al., 2000; Platt et al., 1980; Thubthong, et al., 2005; Whilehill & Ciocca, 2000a; Whilehill & Ciocca, 2000b). Disruptions to early mandibular-driven oscillations have been found to be a negative prognostic predictor of later speech motor delay for individuals with limited mandibular control in early speech, such as individuals with cerebral palsy (Green et al., 2000; Levin, 1999).

1.2.2.3 Jaw Opening and Speech Treatment

The jaw is not only considered the predominant articulator contributing to the development of early speech production but also an important articulator in adult speech production. Lindblom and Sundberg (1971) examined the acoustical consequences of articulatory movements in the speech of a Swedish native speaker and found from the X-ray tracings of the vocal tract that jaw opening resulted in a series of changes of vocal tract configuration, such as a decrease of pharyngeal cavities and tongue height and changes in formant frequencies, suggesting that the extent of jaw opening may affect the demand level required of tongue deformation in vowel formation.

The jaw opening ("open-mouth") technique is one of the common speech therapy approaches used to improve articulation, voice quality, and speech intelligibility (Palmer & Enderby, 2007). Palmer and Enderby (2007), in a review of 23 research articles published from 1966 to 2006 on the subject of speech treatment techniques for individuals with dysarthria, revealed a common belief that speech intelligibility could be improved through behavioral changes in the control of various aspects of speech production such as supraglottal air pressure, vocal tract shape, speech rate, and intensity (Dromey et al, 1995; Ramig et al., 1994; Solomon et al., 2001).

The Lee Silverman voice treatment (LSVT), for example, is a speech and voice program with an indirect prompting or facilitating approach to improve intensity and voice quality for individuals with idiopathic Parkinson disease (PD). Sapir and colleagues (2007) investigated the effect of LSVT on vowel production using 29 individuals with PD and 14 age-matched healthy individuals. After treatment, individuals with PD showed significant positive changes in vocal sound pressure level and perceptual ratings of vowel, indicating that the LSVT program was effective in improving the dysarthric speech for individuals with PD. Solomon, McKee, and Garcia-Barry (2001), in a case study of a 23-year-old male post traumatic brain injury (TBI) 20 months, with mixed hypokinetic-spastic dysarthria, also found a positive effect of LSVT on vocal intensity, articulation, speech rate, and speech intelligibility.

Although the extent of jaw opening was not monitored or necessarily indicated in the training programs mentioned above and thus the differentiation between the impact of jaw opening and that of breath support or increased muscle strength on speech and voice was unclear, the success of treatment programs involving changes in vocal tract configuration necessitates an improved understanding of the effec of jaw opening on speech production.

There is no question that the jaw opening technique, whether directly or indirectly applied, has been used in speech and voice therapy (Boone and McFarlane, 2000) for its potential function in improving loudness and voice quality (Dromey et al., 1995; Ramig et al., 1994; Sapir et al., 2007; Solomon et al., 2001). However, some clinicians argue that the jaw opening approach may have its limitation for treating individuals with motor speech disorders. They believe that the benefit of jaw opening on maximizing intelligibility may be limited by the physical constraints for two reasons. Firstly, dysarthria is a non-linguistic deficit of speech articulation that is characterised by slow, weak, imprecise and/or uncoordinated movements of the speech musculature (Yorkston et al., 1999). Speech in the spastic type of dysarthria, for example, is predominantly slow, imprecise/distorted (Hirose et al., 1982), and laboured with a strained-strangled voice quality, weak tongue strength, and poor endurance (Dworkin & Aronson, 1986). Therefore, it is generally difficult for individuals with muscle hypertonicity, spasticity, or hyperfunction to manipulate jaw movements and thus less adept at, if not aversive to, the usage of the jaw opening approach to increase the accuracy and precision of speech production. Secondly, the jaw opening approach may aggravate muscular weakness or fatigue in patients suffering from severe muscular weakness or hypofunction. To substantiate any speculation derived from clinical observations and prepare for further investigation on the application of the jaw opening approach on dysarthric patients, normative data is needed first to determine how jaw opening may impact on articulatory movements and vocal parameters.

1.2.2.4 Summary

Jaw opening approach is a common facilitating technique used to reduce generalized vocal hyperfunction and improve overall voice quality or speech intelligibility. As findings from treatment efficacy studies have indirectly shown the positive effect of jaw opening approach on speech and voice, more direct investigation on the effect of this approach is needed to determine whether jaw opening can reduce the degree of motor demands for speech production.

1.2.3 Speech Measurement

Speech articulatory movement has been studied through kinematic (Green et al., 2000; Green et al., 2002; Grigos et al., 2005; Maner et al., 2000; Walsh & Smith, 2002), electromyography (Clark et al., 2001; Hough & Klich, 1998; Walsh & Smith, 2002; Wohlert & Hammen, 2000), and acoustic (Bradlow et al., 1996; Fourakis, 1991; Moon & Lindblom, 1994; Tsao et al., 2006; Weismer et al., 2001) measurement.

1.2.3.1 Movements and Muscle Activities

Articulatory movements have been studied using a two or three-dimensional visual tracking device to yield kinematic measures of lip and jaw, such as displacement (Green et al., 2000; Green et al., 2002; Walsh & Smith, 2002), velocity (McClean, 2000), duration (Grigos et al., 2005), and spatiotemporal index, which is a trajectory analysis parameter reflecting the regularity and stability of speech movement (Smith & Goffman, 1998; Smith et al., 2000; Smith & Kleinow, 2000; Walsh & Smith, 2002). Walsh and Smith (2002) employed these measures to investigate the variation of motor control of speech articulation in 120 adolescents and adults, with equal number of females and males in four age groups (i.e., 12, 14, 16, and 21-year-old groups), and found that adolescents exhibited more variable articulatory trajectories of lip and jaw movements, smaller displacement, lower velocities, and longer durations at the phrase level in their speech than adults. It appears that tracking the lip and jaw movements allows for a relatively reliable observation on the subtle changes in the extent and stability of articulatory movement.

The temporal relationship between muscle activities and the strength of activation in each muscle or muscle group can be monitored through electromyographic (EMG) recordings of the electrical activity in the muscles to provide important information regarding the role of individual muscles or synergistic muscle groups towards the generation of active forces for speech movement (Wohlert & Hammen, 2000). For example, it has been shown in an EMG and acoustic study of 89 normal children and young adults that the trial-to-trial variability of lip muscle activity revealed a trend of developmental changes (Wohlert & Smith, 2002). As a linear normalisation technique, however, the EMG technique presents challenges in measuring speech activities, which involve nonlinearities. It is also difficult to infer from EMG signals the activity of specific muscles due to a fairly gross measure in muscle activity (Wohlert & Hammen, 2000) and some methodological limitations in the placement of the EMG electrodes.

1.2.3.2 Acoustic Measurement of Speech Articulation

Acoustic recording of the speech sounds emitted from the mouth is a non-invasive and non-intrusive way of monitoring speech articulation. Acoustic measures of the overall speech function may include time-based measures, such as voice onset time (VOT), consonant or vowel duration, and fundamental frequency (F0), as well as spectral measures such as formant frequencies (Kent & Kim, 2003;

Kent et al., 1999; Wambaugh et al., 1996). There are reportedly over 30 acoustic parameters which can be derived through acoustic analysis (Kent & Kim, 2003).

Voice onset time, defined as the time between the release of the closure for a plosive to the onset of voicing in the following vowel (Auzou et al., 2000), is an objective temporal acoustic measure proposed by Lisker and Abramson (1964) to differentiate between voiced and voiceless plosives. The measure of VOT has been adopted widely to compare the speech timing and coordination patterns between normal individuals and those with speech disorders (Auzou et al., 2000). In Grios et al.'s (2005) study, VOT measures in children were found to vary and progress gradually to adult forms as modification in the timing relationship between laryngeal and oral coordination develops, suggesting that measures of VOT may reflect the developmental changes in articulator movements and motor control skills.

Other acoustic measures can also be related to the physiological subsystems of speech production. For example, the acoustic measure of the F0 contour provides a direct link between laryngeal function and speech intonation, which is related to prosody and intelligibility. Schlench, Bettrich, and Willmes (1993) studied the prosody of 84 German-speaking adults (30 females and 54 males) with dysarthria (including flaccid, spastic, hypokinetic, ataxic, mixed, and non-classifiable types) and 154 normals (73 females and 81 males) and reported that individuals with severe dysarthria exhibited shorter tone units and higher mean F0 than people with mild dysarthria or no motor speech disorders. They concluded that F0 is a sensitive and reliable acoustic parameter for evaluating competence of pitch control in spontaneous speech and thus a means for diagnosing dysarthric speech and monitoring treatment effects.

From the frequency-based representation of an acoustic signal, formants can be identified as peaks representing concentration of spectral energy. The formant patterns of vowels have been shown to reflect not only the phonetic quality of voiced sounds but also articulatory placement (Fry, 1979; Kent & Kim, 2003; Liu et al., 2005; Miller, 1989; Nearey, 1989; Turner et al., 1995). Formants 1 and 2 (F1 and F2), in particular, have been shown to provide an important basis for vowel differentiation (Fry, 1979; Kuiper & Allan, 1996; Miller, 1989; Nearey, 1989; Ito et al., 2001). With their respective correspondence to tongue height and advancement, the frequency values of F1 and F2 have also been used to gauge the accuracy of vowel articulation (Fry, 1979) and vocal tract configuration (Baken & Orlikoff, 2000). Although it has been argued that the loci of F1 and F2 may not be sufficient for defining vowel quality due to a high degree of within and between-subject variations (Ito et al., 2001), formant frequency has generally been considered the most significant parameter necessary to identify vowel characteristics.

1.2.3.3 Vowel Space and Speech Intelligibility

The area of vowel space, a F1-F2 frequency plot of three corner vowels, has been shown to be related to speech intelligibility scores. Peterson and Barney (1952) investigated how 10 vowels in monosyllabic words (with vowels embedded in the nonsense word /h_d/) produced by 76 general American English speakers, including 33 male and 28 female adults and 15 children, were perceived by 70 adult listeners in a vowel differentiation task. It was found that all vowels could be clearly plotted in relatively isolated areas in the plane with F1 and F2 on the two axes. This finding indicated that vowel differentiation was dependent on the loci of the F1 and F2 frequencies of a vowel. Nearey (1978) used the vowel space (i.e., vowel triangle) of vowels /i, a, u/ in the F1-F2 plot to relate the overlaps between vowel categories to problems in vowel differentiation. It has also been shown that a highly intelligible speaker was characterized by an increase in the vowel space area, with F1 covering a broad frequency range (Bradlow et al., 1996; Smiljanić & Bradlow, 2005). Bradlow, Torretta, and Pisoni (1996) studied how the global characteristics (e.g., gender, F0 and speaking rate) and fine-grained acoustic-phonetic talker-characteristics (e.g., vowel space) were related to speech intelligibility in 20 normal American English speakers (10 males and 10 females). Female talkers were found to be more intelligible than male talkers. No correlation was found between speaking rate and speech intelligibility. Most importantly, talkers with a larger vowel space were found to be more intelligible than those with reduced spaces, showing that a talker's vowel space was a useful acoustic-phonetic predictor of overall speech intelligibility for normal talkers.

Many acoustic-perceptual studies have shown that vowel space area is positively correlated with the speech intelligibility in individuals with dysarthria (Ansel & Kent, 1992; Jeng, 2000; Liss et al., 2000; Liu et al., 2005; Platt et al., 1980; Turner, et al., 1995; Weismer et al., 2001). Vowels produced by dysarthric speakers are often distorted, simplified, or substituted due to neuropathophysiological deficits, such as reduced strength, increased muscle tone, or weakness of orofacial structures (Duffy, 2005; Pena-Brooks & Hegde, 2000). Platt, Andrews, Young, and Howie (1980) investigated the articulatory impairment and speech intelligibility in 50 cerebral-palsied adults (32 spastic and 18 athetoid males, aged from 17 to 55 years) and concluded there was generally a limited vowel-articulation tract space in cerebral-palsied dysarthric adults due to poor tongue posture. Specifically, it was shown, in both spastic and athetoid groups, that vowels /i/, /æ/ and /a/, which required the tongue shape to be formed at the extreme positions in the vocal tract for an accurate vowel production, were not produced as correctly as other vowels.

A positive relationship between vowel space and speech intelligibility has been shown in individuals with motor speech disorder associated with CP and hypokinetic and ataxic dysarthria (Liss et al., 2000; Liu et al., 2005). Inappropriate tongue and jaw movement have been considered the main causes for the reduction of the articulatory working space for vowels (Ansel & Knet, 1992). Liu, Tsao, and Kuhl (2005) examined the phonetic contrasts in the speech production of 20 young male Mandarin-speaking CP adults, aged from 17 to 22 years with normal hearing and intelligence, and found that the average vowel space of the CP subjects were significantly smaller than that of 10 age-matched normal controls. The reduced vowel space was interpreted as a reflection of restricted lingual movement, such as tongue elevation and/or front-back retraction, and a deficit in timing control. In general, the vowel space, which relates strongly to vowel, word, and speech intelligibility for individuals with dysarthria, has been considered to have great potential for predicting the speech intelligibility of individuals with dysarthria (Turner et al., 1995; Weismer et al., 2001).

Similar findings of vowel space and speech intelligibility have also been reported in studies of speakers with Amyotrophic Lateral Sclerosis (ALS) (Turner et al.,1995; Weismer et al., 2001), Parkinson's disease (Weismer et al., 2001; Tjaden & Wilding, 2004), TBI (Ziegler & von Camon, 1983), and multiple sclerosis (Tjaden & Wilding, 2004). For example, Turner et al. (1995), in examining the relationship between vowel space area, speaking rate, and speech intelligibility in a group of nine subjects with ALS (five males and four females, aged from 34 to 68 years) and nine age and gender matched controls using acoustic and perceptual measurements of connected speech, found dysarthric speakers with ALS to exhibit reduced vowel space and increased speech intelligibility. Speech rate was not found to be related to vowel space in an acoustic-perceptual study by Tsao, Weismer and Iqbal (2006) of 30 healthy adults, aged from 18 to 35 years with a US midwest dialect, although slowing speaking rate has been found to improve speech intelligibility for dysarthric speakers

(Duffy, 2005). A breathing technique using increased jaw opening to increase the lung volume initiation level has been proven beneficial to speech intelligibility, as reflected in increased vowel space (Gao et al., 2004; Weismer et al., 2001). Watson et al. (2003), in a study of eight young healthy American English speaking women, aged from 18 to 35 years with no formal voice training, found that vowel space was significantly smaller for vowels with voice initiated at low lung volume levels than those at typical lung volume level, suggesting that vowel space may be affected by the aerodynamic aspect of voice production, which is related to laryngeal behaviours.

1.3 Research Outline

Based on current understanding of the classification of phonetic complexity in relation to speech mechanism and the direct or indirect usage of jaw opening in speech treatment, this study employs a selection of instrumental measures to investigate the relationship between jaw opening and phonetic complexity. The research question and the purpose, importance, aims, and hypotheses of the study are described as follows.

1.3.1 Statement of the Problem

The jaw opening technique has been applied clinically to improve speech and voice production as previously mentioned. However, there is a lack of understanding of how it works: whether the jaw opening effect is (a) mainly motor-based, as having a mechanical effect on reducing the motor demands required for the phonetic complexity associated with the target sounds, or (b) at least partly, if not all, perceptually-based, as in inducing an acoustic effect of increasing the differentiation between speech sounds. Specifically, four questions are posed: (1) Does jaw opening result in increased vowel space, which has been found to reflect increased vowel differentiation or speech intelligibility? (2) How does jaw opening impact on phonetic complexity, as may be reflected in changes of articulatory and vocal behaviours in different phonetic contexts? (3) Is the jaw opening effect on laryngeal behaviour, if any, affected by the phonemic use of fundamental frequency as in a tone language? (4) Is the jaw opening effect on speech production universal or language-specific?

1.3.2 Purpose of the Study

The current study employs a group design to examine the impact of jaw opening on articulatory and vocal behaviours. The purpose of the study is to provide empirical evidences to determine whether increased jaw opening, a form of global adjustment to the vocal tract configuration, can reduce phonetic complexity to improve speech and voice quality and how it may interact with other factors, such as phonetic context and language.

1.3.3 Importance of the Study

In traditional articulation therapy, the technique of exaggerating jaw opening or a full articulation, also known as hyper or over-articulation, has been shown to improve speech intelligibility for individuals with dysarthria (Freed, 2000), especially those with flaccid dyarthria (Swigert, 1997). This study will provide instrumental measures needed to demonstrate the effect of jaw opening on speech and voice production. The normative data provided in this study will strengthen the rationale for further investigation in support of an evidence-based practice regarding the usage of a jaw opening technique in individuals with motor speech disorders.

Speech therapy for individuals with dysarthria associated with CP often involves speech motor training to improve the coordination of oral, laryngeal and pharyngeal musculatures, modification of communicative behaviours in response to communication failure, and breath-group training to improve and maintain breath support for speech (Love et al., 1980; Pennington et al., 2006; Solomon & Charron, 1998). As the jaw opening strategy may be an appropriate speech therapy technique for improving the speech intelligibility of dysarthric individuals, investigation on how this facilitating technique could affect the articulatory and laryngeal movement as well as the speech acoustics will lead to improved understanding of the role of vocal tract configuration and its interaction with the vocal folds in reducing phonetic complexity in speech production.

1.3.4 Aims and Hypotheses

This study aims to provide a cross-language and cross-system view of the problem regarding the effect of jaw opening on speech and voice production. From the kinematic and acoustic perspective, it is hypothesized that the jaw opening technique would result in vowel space expansion and increased phonatory stability. The effect of jaw opening in reducing phonetic complexity can be demonstrated through its interaction with phonetic context on the induced changes of the speech and voice measures. In particular, it is hypothesized that the positive jaw opening effect on the experimental measures would be most evident for phonemes involving tongue movements because of the dependence of larynx height on tongue positioning.

Chapter 2. METHODOLOGY

This chapter provides a detailed description of the study design, including subject information, instrumentation setup, data collection procedures, analysis methods, and the definition and reliability of the experimental measures.

2.1 Participants

A convenience sampling method was used to recruit residents from the local community (Christchurch, New Zealand) to volunteer as participants. Participants were 20 healthy non-smoking adults, including 10 New Zealand English (Mean = 36.5 years, SD = 14) and 10 Mandarin (Mean = 27.5 years, SD = 9.3) native speakers, with five females and five males in each language group (see Appendix 1). Participants had neither history nor any sign of neurological disease, trauma to the oro-facial structure, habitual temporo-mandibular joint dislocation, or speech, language, voice, or hearing problems.

2.2 Materials

The participant's task was to verbalize monosyllabic CV couplets in his/her native language. The English and Mandarin CV couplets were compiled separately with a selection of consonants followed by one of the three corner vowels (/i, a, u/) following the phonotactic rules of English and Mandarin respectively. Consonants were chosen if they would allow for direct contrasts in voicing or the place and manner of articulation between phonemes within a language or a cross-language comparison on phonemes with compatible place and manner of articulation in English and Mandarin.

For both language groups, the reading materials included (1) an initial short list of CV couplets, each in one trial, including almost all consonant phonemes in the target language followed by vowel /a/, (2) a long list of CV couplets, each in four (for those that have been included in the short list) or five trials, including a selection of consonants and three vowels /i, a, u/, and (3) an exit short list of 10 different CV couplets, each in one trial, randomly chosen from all the CV combinations included in the previous short and long list. These lists were designed as such to keep recording time within a reasonable time frame, covering (1) as many phonemes as possible in the same vowel context with only one trial and (2) five trials of a selection of phonemes allowing for some contrasts in voicing and place of articulation. The main difference between Mandarin and English CV lists was the inclusion of tonemes in Mandarin, with the two Mandarin short lists incorporating only Tone 1 while the Mandarin long list consisting of all four tones using the /l/-initiated couplets.

The order of the CV couplets was randomized. Two versions of the initial short list were prepared with the same items in different random orders. With a random selection procedure, half of each language group were assigned to reading only version A and half to version B of the short list. Specific descriptions of the lists for the two language groups are provided as follows.

2.2.1 English CV Couplets

The English short list consisted of CV couplets incorporating vowel /a/ and 19 consonants, including all English consonants except for two semivowels /j/ and /w/, a nasal /η/, a retroflex /r/, and a palatal fricative /ʒ/. The semivowels were excluded because the production mechanism for them was close to that for vowels. The other three consonants were excluded because they were prohibited by the phonatactic constraints in English or Mandarin from immediately preceding a single vowel /a/. The English long list consisted of CV couplets containing (1) each of the 4 consonants, /p, b, t, d/, followed by one of the two vowels, /i/ or /u/, in five trials each and (2) each of the 6 consonants, /p, b, t, d, ʧ, ʤ/, followed by vowel /a/, in four trials each. The couplets involving vowel /a/ and each of the two consonants, /ʧ/ and /ʤ/, were added to allow for similar comparisons in Mandarin. In total, the English short list contained 19 items (19 consonants X 1 vowel X 1 trial), the English long list 64 items [(4 consonants X 2 vowels X 5 trials) + (6 consonants X 1 vowel X 4 trials)], and the exit list 10 items.

2.2.2 Mandarin CV Couplets

The Mandarin short list consisted of one trial of CV couplets incorporating Tone 1, vowel /a/, and 17 consonants, including all Mandarin consonants except for those that were not allowed, due to the phonatactic constraints in Mandarin, to immediately precede vowel /a/, including one retroflex, /r/ (ㄖ), one palatal fricative, /ɕ/ (ㄒ), and two palatal affricates, /tɕ/ (ㄐ) and /tɕ'/ (ㄑ). The Mandarin long list consisted of CV couplets incorporating (1) Tone 1, vowel /i/, and five consonants, including /p'/ (ㄆ) , /p/ (ㄅ), /t'/ (ㄊ), /t/ (ㄉ), and /l/ (ㄌ), in five trials each, (2) Tone 1, vowel /a/, and seven consonants, including /p'/ (ㄆ) , /p/ (ㄅ), /t'/ (ㄊ), /t/ (ㄉ), /l/ (ㄌ), /tʂ/ (ㄓ), and /tʂ'/ (ㄔ), in four trials each, (3) Tone 1, vowel /u/, and five consonants, including /p'/ (ㄆ) , /p/ (ㄅ), /t'/ (ㄊ), /t/ (ㄉ), and /l/ (ㄌ), in five trials each, and (4) Tones two to four, vowel /i/, /a/, and /u/, and one consonant /l/ (ㄌ), each in five trials. In total, the Mandarin short list contained 17 items (17 consonants X 1 vowel X 1 trial), the Mandarin long list 123 items [(5 consonants X 1 vowel X 1 tone X 5 trials) + (7 consonants X 1 vowel X 1 tone X 4 trials) + (5 consonants X 1 vowel X 1 tone X 5 trials) + (1 consonant X 3 vowels X 3 tones X 5 trials)], and the exit list 10 items.

2.2.3 Rankings of Phonetic Complexity

To show that different consonant contexts may represent different levels of phonetic complexity, the ranking of phonetic complexity for the English and

Mandarin consonants used in this study are presented in Tables 2 and 3 respectively. These tables show the rankings based on three different ranking systems and the total of the three scores for each phoneme, with a lower ranking score indicating a lower level of phonetic complexity. The assignment of these phonetic complexity rankings is based on the concept of phonetic complexity as viewed from the kinematic and developmental perspectives reported in the literature (Bauer, 1988; Carterette & Jones, 1974; Prather et al., 1975; Sander, 1972; Stoel-Gammon, 1985). From the kinematic perspective, phonetic complexity can be calculated with a formula of phonetic product, which was based on a classification scheme modified from that as proposed by Bauer (1988), resulting in seven place categories ranked in phonetic complexity from one to six, with palatal being ranked the lowest, followed in order by velar and glottal, bilabial, labio-dental, apical (alveolar), and retroflex. Based on the ordering of the development of the manner of articulation, each phoneme can be assigned a grade of phonetic complexity according to the ordering of the first occurrence for the manner of articulation in the general sound development, starting with nasals as being the earliest to develop and followed in order by plosives, fricatives, affricates, and laterals (see Tables 2 and 3). Based on the age of acquisition for individual consonants as charted by Sander (1972, p. 62), the consonants used in this study can be ordered into nine grades (see Tables 2 and 3).

2.3 Instruction to Participants

Participants were asked to say, (1) each of the CV couplets included in the initial short list and the long list at their normal pitch, loudness, rate, and posture, (2) repeat the same sequence of productions using an exaggerated jaw opening posture, and (3) finish off by saying the items on the exit short list using normal jaw posture. At the beginning of the "exaggerated jaw opening" session, participants received from the experimenter a verbal instruction "Open your mouth as wide as possible while saying the word" and a real life demonstration.

For both language groups, each CV couplet was presented individually on a piece of paper in A4 size (i.e., 21 cm X 29.7 cm) placed in front of the participant. For the English group, English letters in big font size and two English words presented in a smaller font size at the right corner of the page were used to cue for the target CV couplet. For the Mandarin group, each CV couplet was presented without cueing words and Taiwanese phonetic symbols instead of English letters were used.

2.4 Instrumentation

A multi-system digital recording setup was employed to simultaneously record acoustic and electroglottographic (EGG) signals and marker-based video tracings of jaw and lip movements.

2.4.1 Simultaneous Acoustic and EGG Recording

The acoustic recording device included a headset condenser microphone (AKG C420, Austria) and a mixer (Eurorack MX602A, Behringer), which was used as a microphone amplifier. The EGG device (Kay Elemetrics Model 6103, USA) included a connector box and two round shaped electrodes, each with a diameter of 3.5 cm. A 12-bit multichannel A/D converter (National Instrument DAQCard-AI-16E-4, USA) equipped with a SCB-68 68-pin shielded connector box was housed by a laptop computer (HP Compaq nx7400, Taiwan).

For acoustic recording, the headset microphone was placed off-axis at a distance of approximately 5 cm from the participant's mouth. The microphone was connected to the mixer and the output of the mixer was connected to the A/D converter via the first channel of the connector box. For EGG recording, the two EGG electrodes were placed on the skin over the two lamina of the thyroid cartilage and held in place by velcro tapes fastened around the participant's neck. The output of the EGG device was connected to the A/D converter via the second channel of the connector box. The connector box coupled with the A/D converter contained a filter for each channel, with acoustic signals low-passed at 20 KHz and EGG signals at 5 KHz.

A locally developed algorithm written in MATLAB 6.0 (The Mathworks, Inc., USA) was used for digitization of acoustic and EGG signals and for analysis of the EGG signals. A time-frequency analysis software (TF32; copyright: Paul Milenkovic, 2000, USA) was used for acoustic analysis.

2.4.2 Marker-Based Video Facial Tracking

The marker-based video facial tracking system included a mini-camera (1/4 CMOS PC Camera, Taiwan) equipped with two infrared LEDs (light-emitting diodes) on both sides of the lens, a tripod with an extended arm of wooden board added on the top to hold the camera, a laptop (Acer Aspire 5570Z, Taiwan), and reflective materials (in silver colour) cut into eight small round dots. The marker dots, with a diameter of 6 mm each, were secured on the participant's face, with four dots attached to a black board (4 cm X 4 cm) which was taped to the participant's forehead, one dot on the nose tip, two dots on the right and left sides of the lips, and one dot on the chin in the vicinity of the mandibular symphysis. A locally developed program written in C++ was used to acquire video images and process the tracings of the dots on the chin and on the sides of the lips in relation to the calibration dots on the forehead and the nose.

2.5 Procedures

The participant was seated in a double-walled room (noise level was under 40 dB SPL), on a chair against a wall covered with a sheet of black cloth. The experimenter briefly explained the general requirement for the participant's task and asked the participant to sign the consent form. After the experimenter put the electrodes on the participant's neck, the microphone on the participant's head, the marker dots on the participant's face, and the camera in front of the participant, the participant was asked to perform some practice trials to allow the experimenter to adjust the placement of the camera and the EGG electrodes. After the instrumental setup was adjusted, the participant was asked to perform the participant's task. During the recording session, one experimenter was responsible for checking if the participant performed the task as instructed and for flipping the reading pages placed in front of the participant while a second experimenter operated the recording system and gave verbal prompting to elicit the participant's speech production.

The between-trial pause was around three seconds in average and a short two-minute break was given after every 36 trials for the participant to relax or take a sip of water. The recording time was normally 30 minutes for an English speaker and one hour for a Mandarin speaker. The acoustic-EGG signals were directly digitized and stored as separate wave files and the facial tracking data for lip spreading and jaw opening were saved together as text files for later analysis.

2.6 Measurement and Data Analysis

Experimental measures in this study included measurement of three types of signals: video facial tracking of jaw opening, acoustic, and EGG. In total, 4,660 tokens were recorded (1,760 tokens for the English and 2,900 tokens for the Mandarin groups respectively) for each of the three types of signals. The definitions of the experimental measures and the data analysis method used to derive these measures are described as follows.

2.6.1 Jaw Opening

The facial tracking signals were analyzed using a locally developed algorithm written in MatLab to yield measures of maximum jaw displacement. Figure 1 shows a display of the tracings for lip spreading and jaw opening, with time on the X-axis and amplitude on the Y-axis. The tracing for lip spreading represents changes of the distance between the dots on the two sides of the mouth, with a higher value indicating a larger degree of lip spreading. The tracing for jaw opening represents changes of the distance between the dots on the chin and on the nose, with a higher value indicating a larger degree of jaw opening. During video recording, the displacement values were automatically calibrated against the reference dots placed on the forehead and thus the displacement values were shown as real-life size.

To derive the maximum jaw displacement during vowel production, the experimenter displayed the recorded video tracking signals on the computer screen and used the cursor to locate the highest peak in the selected segment of the time waveforms and the baseline corresponding to the displacement of the jaw at rest. The values were entered into a spreadsheet for automatic calculation of the extent of jaw opening, which was the absolute value of the difference between the maximum and the baseline values of the tracing for jaw movement. It is noteworthy that identification of the maximum jaw displacement during vowel production required confirmation through the presence of a time-aligned excursion of the tracing of lip spreading and an additional verification through viewing of the corresponding video images. As shown in Figure 2, an additional jaw opening peak could be observed in the case when a participant opened his/her mouth before saying the CV couplet. Since this non-speech jaw displacement could at times exceed the jaw displacement during phonation, as shown in the right graph of Figure 2, viewing of the video images was necessary when multiple peaks were observed.

2.6.2 Acoustic Measures

The acoustic signals were analyzed using the TF32 software to derive measures of consonant length (same as VOT for plosives), F0, phonatory stability (percent jitter, percent shimmer, and signal-to-noise ratio), and frequencies of formants one and two.

2.6.2.1 Voice Onset Time/Consonant Length (C-Length)

Consonant length (C-Length) can be defined as the time from the first occurrence of the consonant sound energy to the onset of voicing in the following vowel. In plosives, consonant length is equivalent to VOT, which is the time between the release of an oral closure and the onset of the voicing in the following vowel. To measure VOT or consonant length, the experimenter displayed the time waveforms and spectrogram of the acoustic signal using the TF32 software and cursor-selected the target segment to yield the time measurement. As shown in Figure 3, the change of intensity or regularity of the signal shown in the time waveforms and the traces of formant frequencies, as well as the shadow of the short vertical bars at the bottom or the long stripes indicative of harmonics in the vicinity of the beginning of a vowel in the spectrogram, provided cues for the determination of the C-Length or VOT. In this study, the onset of voicing is defined as the first occurrence of the automatically generated traces of formant frequencies on a broadband spectrogram (bandwidth = 300 Hz).

2.6.2.2 Fundamental Frequency

Fundamental frequency of vocal fold vibration is an important acoustic feature reflecting laryngeal movement and speech prosody. Since F0 varies continuously during speech, an average F0 was measured in this study from the middle steady portion of the vowel segment to avoid onset and offset variations.

2.6.2.3 Phonatory Stability

The same segment selected to yield the F0 measure was also used to derive measures of percent jitter (%jitter), percent shimmer (%shimmer), and signal-to-noise ratio (SNR). Percent jitter represents cycle-to-cycle frequency variation, %shimmer cycle-to-cycle amplitude variation, and SNR the ratio between the energy the periodic components and the noise components (Milenkovic, 1987). A higher value of %jitter or %shimmer or a lower value of SNR typically suggests a lower level of phonatory stability or voice quality (Gelfer, 1995).

2.6.2.4 Formant Frequencies

The F1 frequency has been found to be related to tongue height, with a lower F1 indicating a higher tongue positioning (Monsen, 1976) or a lower degree of pharyngeal constriction (Baken & Orlikoff, 2000), and the F2 frequency related to tongue advancement, with a lower F2 indicating a more backward tongue placement or a greater degree of posterior oral constriction (Baken & Orlikoff, 2000). The experimenter cursor-selected a time slice from the spectrogram corresponding to the midsection of the vowel and used an automatic peak picking algorithm to locate the lowest two (in terms of the frequency value) spectral peaks on the LPC (Linear Prediction Coding) spectrum. With the frequency values of F1 and F2 for vowels /i/, /a/, and /u/, a formula as described by Liu et al. (2003, p. F4) was used to calculate vowel space area:

"Vowel space area = ABS{[F1i*(F2a-F2u)+F1a*(F2u-F2i)+F1u*(F2i-F2a)]/2}

where ABS is absolute value, F1i symbolises the F1 value of vowel/i/, and so on."

2.6.3 Electroglottographic Measures

The glottal parameters F0, open quotient (OQ), and speed quotient (SQ) were measured using the EGG signal analysis software.

2.6.3.1 Average F0

An additional measure of the average F0 was derived from the EGG signals for a comparison with that derived from the acoustic signals. The F0 derived from the EGG signals was obtained by dividing the number of EGG cycles in the selected vowel segment by the time selected (Lim et al., 2006).

2.6.3.2 Speed Quotient and Open Quotient

Measures of SQ and OQ were obtained from EGG signals to reflect laryngeal behaviours. A 90% method was used to define the various phases in a glottal cycle, with the time between 10 and 90% of the whole amplitude range of a glottal cycle during glottal opening defined as the opening phase, that during glottal closing the closing phase, and the time between the two 90% points the open phase (Lim et al., 2006). The SQ is defined as the ratio between opening phase and closing phase and the OQ the ratio between open phase and cycle period.

2.7 Statistical Analysis

A series of two-way ANOVAs were performed on the experimental measures for individual participants in different vowel contexts separately to determine whether there was a task effect (normal versus exaggerated jaw opening), consonant effect, or a task-by-consonant interaction effect. For the Mandarin data, an additional series of two-way ANOVAs were performed on the CV couplets initiated with /l/ to determine the effects of task, tone, and their interaction. The average values for each individual were further combined and submitted to a series of two-way Repeated Measures (RM) ANOVAs to yield a group-based set of comparisons on these effects. Post-hoc pairwise comparison procedures were conducted when a significant effect was detected. The significance level was set at 0.05. SigmaStat 3.5 (Systat Software, Inc., USA) was used for all statistical analysis.

2.8 Reliability

To assess measure-remeasure reliability, 20% of the total tokens of acoustic signals were reanalysed using the same measurement procedure as used in the first measurement. Results from a series of Pearson Product Moment correlation procedures performed on the two sets of corresponding measures revealed a relatively high measurement reliability for C-Length ($r = 0.983$), F1 ($r = 0.973$), F2 ($r = 0.965$), and SNR ($r = 0.815$), and moderately high to adequate for F0 ($r = 0.729$), %shimmer ($r = 0.673$), and %jitter ($r = 0.582$).

Chapter 3. RESULTS

Results of the two-way ANOVAs performed on the experimental measures for individual participants in different vowel contexts separately to determine whether there was a task effect, consonant or tone effect, or a task-by-consonant or task-by-tone interaction effect for individual subjects were shown in Appendices 2 to 31. Results of the two-way RM ANOVAs performed on the averaged group data to determine the language, task, consonant, and tone effects for each of the three vowels separately were shown in Tables 4 to 7.

3.1 Extent of Jaw Opening

The extent of jaw opening was generally found to vary by task and consonant but not by language or tone.

3.1.1 Language Effect

Results of two-way RM ANOVAs performed on measures of the extent of jaw opening averaged over all consonant contexts revealed, for each of the three vowels, a significant task effect but no significant language or language-by-task interaction effects (see Table 4).

3.1.2 Task Effect

Based on results from the averaged group data, the extent of jaw opening for the normal task was significantly smaller (/i/: 8.8 mm, /a/: 12.7 mm , /u/: 5.2 mm) than that for the exaggerated jaw opening task (/i/: 12.3 mm, /a/: 23.9 mm, /u/: 8.4 mm). For the English group, results of two-way RM ANOVAs performed on measures of the extent of jaw opening in the 4 consonant contexts (/p, b, t, d/) for vowels /i/ and

/u/ and in the 19 consonant contexts (/p, b, t, d, k, g, f, v, ð, θ, s, z, ʃ, tʃ, ʤ, h, m, n, l/) for vowel /a/ all revealed a significant task effect (see Table 4). For the Mandarin group, results of two-way RM ANOVAs performed on measures of the extent of jaw opening in the 5 consonant contexts (/p', p, t', t, l/) for vowels /i/ and /u/ and in the 17 consonant contexts (/p', p, t', t, k', k, f, s, ʂ, ts, ts', tʂ', tʂ, h, m, n, l/) for vowel /a/ all revealed a significant task effect except for vowel /u/ (see Table 5).

3.1.3 Consonant Effect

For the English group, results of two-way RM ANOVAs performed on measures of the extent of jaw opening in the 4 consonant contexts for vowels /i/ and /u/ and 19 consonants for vowel /a/ revealed a significant consonant effect only for vowel /u/ (see Table 5). For vowel /u/ in the English group, post-hoc pairwise comparison procedure using the Holm-Sidak method revealed that the extent of jaw opening in the /p/ context was significantly larger than that in all the other 3 consonant contexts (/t, b, d/).

For the Mandarin group, results of two-way RM ANOVAs performed on measures of the extent of jaw opening in the 5 consonant contexts for vowels /i/ and /u/ and in the 17 consonant contexts for vowel /a/ all revealed a significant consonant effect except for vowel /u/ (see Table 6). However, post-hoc tests failed to reveal any significant difference on the extent of jaw opening between different consonant contexts.

3.1.4 Tone Effect

For the Mandarin group, results of two-way RM ANOVAs performed on measures of the extent of jaw opening in one consonant (/l/) context revealed a significant tone effect only for vowel /a/ (see Table 7). However, post-hoc tests failed to reveal any significant difference on the extent of jaw opening between different tones.

3.2 Fundamental Frequency

Fundamental frequency was generally found to vary by task, consonant, and tone but not by language.

3.2.1 Language Effect

Results of two-way RM ANOVAs performed on F0 averaged over all consonant contexts revealed, for each of the three vowels, a significant task effect but no significant language or language-by-task interaction effects (see Table 4).

3.2.2 Task Effect

As shown in Figures 4, the average F0 in the exaggerated jaw opening task was significantly higher than in the normal task across all vowels. However, results of two-way RM ANOVAs performed on F0 in the selected consonant contexts for the English group failed to reveal any significant task effect (see Table 5 and Figure 5). In contrast, results of two-way RM ANOVAs performed on F0 measures in the selected consonant contexts for the Mandarin group revealed a significant task effect only for vowels /i/ and /u/ (see Table 6 and Figure 5). For the vowels /i/ and /u/ in the Mandarin group, post-hoc tests revealed that F0 was significantly higher for the exaggerated jaw opening posture than for the normal posture across all consonants.

3.2.3 Consonant Effect

For the English group, results of two-way RM ANOVAs performed on F0 in the selected consonant contexts failed to reveal any significant consonant effect (see Table 5).

For the Mandarin group, results of two-way RM ANOVAs performed on F0 in the selected consonant contexts revealed a significant consonant effect and a significant consonant-by-task interaction effect for vowels /i/ and /a/ (see Table 6). For vowel /i/ in the Mandarin group, post-hoc tests revealed that F0 in the /t'/ context was significantly higher than that in other consonant contexts (/p, t, l/) and that F0 in the /p'/ context was significantly higher than that in the /l/ context for the normal task while no significant between-consonant difference was found for the exaggerated task, suggesting that phonation following aspirated consonants in Mandarin was associated with higher F0 in the normal task (see Figure 6.1.1). For vowel /a/ in the Mandarin group, post-hoc tests revealed that more between-consonant comparisons on F0 were significant in the exaggerated jaw opening task than in the normal task (see Figure 6.1.2), with aspirated consonants generally showing higher values of F0 than unaspirated ones.

3.2.4 Tone Effect

For the Mandarin group, results of two-way RM ANOVAs performed on measures of F0 in one consonant (/l/) context revealed a significant tone effect across all vowels and a significant tone-by-task interaction effect for vowels /i/ and /u/ (see Table 7).

For vowel /i/, post-hoc tests revealed that the exaggerated jaw opening task resulted in significantly higher F0 than the normal task only for Tone 1 and that the difference in the average F0 was significant between all four tones except for that between Tones 2 and 4 in the exaggerated jaw opening condition (see Figure 7.1).

For vowel /a/, post-hoc tests revealed that all tones were significantly different in F0, regardless of task, with Tone 1 exhibiting the highest F0, followed in order by Tone 4, Tone 2, and Tone 3 (see Figure 7.2).

For vowel /u/, post-hoc tests revealed that the exaggerated jaw opening task exhibited significantly higher F0 than the normal task for Tones 1 and 4 and that the difference in the average F0 was significant, regardless of task, between all four tones except for that between Tones 1 and 4 (see Figure 7.3).

3.3 Phonatory Stability

Voice quality measures, including %jitter, %shimmer, and SNR, were found to vary by language, task, consonant, and tone.

3.3.1 Language Effect

Results of two-way RM ANOVAs performed on both %jitter and SNR averaged over all consonant contexts revealed a significant language effect for all three vowels and a significant language-by-task interaction effect for vowel /u/ on %jitter and for vowel /a, u/ on SNR (see Table 4). As shown in Figure 5, the Mandarin group tended to exhibit lower %jitter and %shimmer and higher SNR than the English group regardless of task and vowel.

3.3.2 Task Effect

Based on results from the averaged group data, the exaggerated jaw opening task showed significantly lower %jitter and %shimmer and higher SNR than the normal task for vowels /i/ and /u/ (see Figure 4). For the English group, results of two-way RM ANOVAs performed on %jitter and %shimmer measures in the selected consonant contexts revealed a significant task effect for vowels /i/ and /u/ (see Table 5 and Figure 5). For vowels /i/ and /u/ in the English group, the exaggerated jaw opening task was associated with significantly lower %jitter and %shimmer than the normal task. For vowel /u/ in the English group, the exaggerated jaw opening task exhibited significantly higher SNR than the normal task (see Figure 5). Similar results on %jitter (for vowel /u/) and %shimmer were also found for the Mandarin group (see Table 6 and Figure 5).

3.3.3 Consonant Effect

For the English group, results of two-way RM ANOVAs performed on %jitter, %shimmer, and SNR measures in the selected consonant contexts revealed a significant consonant effect only for vowel /u/ on %jitter and %shimmer (see Table 5). Post-hoc tests failed to reveal any significant pairwise comparisons between consonant contexts on %jitter (see Figure 8.1.3) but revealed that %shimmer in /p/ and /t/ were significantly higher than /b/ for vowel /u/ (see Figure 8.2.3).

For the Mandarin group, results of two-way RM ANOVAs performed on %jitter, %shimmer, and SNR measures obtained from vowels in a selection of consonant contexts revealed a significant consonant effect on %shimmer and SNR only for vowel /a/ (see Table 6). For vowel /a/ in the Mandarin group, post-hoc tests failed to revealed any significant pairwise comparisons between consonants for %shimmer (see Figure 6.2.2) but revealed that SNR was significantly higher in the /m/ or /n/ context than in the /f/ context (see Figure 6.3.2).

3.3.4 Tone Effect

For the Mandarin group, results of two-way RM ANOVAs performed on measures of %jitter, %shimmer, and SNR in one consonant (/l/) context revealed a significant tone effect across all vowels (see Table 7). As shown in Figure 9, phonation in Tones 3 and 4 tended to show higher %jitter and %shimmer and lower SNR than that in Tones 1 and 2.

3.4 Speed Quotient and Open Quotient

Glottal measures, including SQ and OQ, were found to vary by language, consonant, and tone but not by task. A significant language effect on OQ was found only for vowel /a/ (see Table 4), with the Mandarin group (mean = 0.36, SD = 0.06) showing a higher OQ than the English group (mean = 0.30, SD = 0.06).

For the English group, a significant consonant effect was found on SQ and OQ for vowel /i/ and on SQ only for vowel /u/ (see Table 5). For vowel /i/ in the English group, phonation in the /t/ context was found to be associated with a significantly lower SQ than that in the /b/ and /d/ contexts (see Figure 10.1.1) and higher OQ than that in the /d/ context (see Figure 10.2.1). For vowel /u/, phonation in the /t/ context was found to have a significantly lower SQ than that in the /d/ context (see Figure 10.1.3).

For the Mandarin group, a significant consonant effect was found on SQ and OQ for vowel /a/ and on SQ only for vowel /u/ (see Table 6). For vowel /a/ in the normal task for the Mandarin group, post-hoc tests revealed that phonation in the /k/ and /n/ contexts was associated with a significantly lower OQ than that in the /k'/ and /f/ contexts (see Figure 11.2) and phonation in the /k/, /n/, and /tʂ/ contexts a significantly higher SQ than that in the /k'/, /h/, and /f/ contexts (see Figure 11.1). For vowel /u/, post-hoc tests failed to reveal any significant pairwise difference between consonant contexts on SQ.

For the Mandarin group, results of two-way RM ANOVAs performed on EGG measures obtained from vowels in one consonant (/l/) context revealed a significant tone effect and a significant tone-by-task interaction effect for vowel /u/ (see Table 7). Post-hoc tests revealed that in the normal task, the SQ in Tone 3 (mean = 0.61, SD = 0.05) was significantly higher than that in Tones 1 (mean = 0.54, SD = 0.08) and 2 (mean = 0.54, SD = 0.10) but not significantly different from Tone 4 (mean = 0.57, SD = 0.05). In the exaggerated jaw opening task, SQ was not significantly different between tones.

3.5 Formant Frequencies and Vowel Space

Formant frequencies were found to vary by language, task, consonant, and tone.

3.5.1 Language Effect

Results of two-way RM ANOVAs performed on formant frequencies averaged across all consonants revealed a significant language effect on F2 for vowel /u/ and a significant language-by-task interaction effect on F2 for vowel /i/ (see Table 4). As shown in Figure 12, the area of vowel space was generally larger in the Mandarin group (vowel space area = 534,285) than in the English group (vowel space area = 301,705), mostly due to a lower F2 value in the Mandarin group for vowel /u/.

3.5.2 Task Effect

Based on the average data from both language groups, a significant task effect was found for vowels /i/ and /a/ (Table 4), with the exaggerated jaw opening task showing significantly lower F1 and higher F2 for vowel /i/ and higher F1 and lower F2 for vowel /a/ as compared with the normal task.

For the English group, results of two-way RM ANOVAs performed on measures of formant frequencies obtained from vowels in a selection of consonant contexts revealed a significant task effect on F1 and F2 for vowel /i/ and on F1 for vowel /a/ and a significant task-by-consonant interaction on F2 for vowel /a/ (see Table 5). Post-hoc tests revealed that the exaggerated jaw opening task was associated with a significantly lower F1 and higher F2 for vowel /i/ but significantly higher F1 for vowel /a/ as compared with the normal task. For vowel /a/ in the English group, the exaggerated jaw opening task showed a significantly lower F2 than the normal task for consonants /k, l, tʃ, ʤ/ (see Figure 13). As shown in Figure 12, these changes resulted in an expansion of vowel space for the exaggerated jaw opening task (396,165) as compared with the normal task (301,705) in the English group. In addition, some preliminary observations on the gender effect in each language group have been made through visual inspection on the average female and male vowel spaces, which revealed that females tended to have a larger vowel space than males for both language groups (see Appendix 32). In both English male and female subgroups (see Appendix 32), the vowel space in the normal task (Males: 224,626, Females: 389,972) was smaller than the exaggerated jaw opening task (Males: 290,250, Females: 516,981).

For the Mandarin group, results of two-way RM ANOVAs performed on formant frequencies obtained from vowels in a selection of consonant contexts revealed a significant task effect on F1 for vowel /a/ and on F2 for vowel /u/ (see Table 6), with the exaggerated jaw opening task showing a significantly higher F1 for vowel /a/ and a significantly lower F2 for vowel /u/ as compared with the normal task. As shown in Figure 12, these changes led to an expansion of vowel space for the exaggerated jaw opening task (586,444) as compared with the normal task (534,285) in the Mandarin group. In both Mandarin male and female subgroups (see Appendix 32), the vowel space in the normal task (Males: 400,642, Females: 686,721) was also found to be smaller than the exaggerated jaw opening task (Males: 454,743, Females: 734,004).

3.5.3 Consonant Effect

For the English group, results of two-way RM ANOVAs performed on formant frequencies obtained from vowels in a selection of consonant contexts revealed a significant consonant effect on F1 and F2 for vowels /a/ and /u/ and, as previously mentioned, a significant consonant-by-task interaction effect on F2 for vowel /a/ (see Table 5). For vowel /a/ in the English group, post-hoc tests revealed a significantly higher F1 in nasals /m/ and /n/ than in almost all other consonants (see Figure 14.1). For vowel /u/ in the English group, post-hoc tests failed to reveal any significant pairwise comparisons between the consonant contexts on F1 (see Figure 14.2). For the vowel /a/ in the English group, post-hoc tests on F2 revealed that more pairwise comparisons between consonants were significant in the normal task (35 out of 171 pairs) than in the exaggerated jaw opening task (11 out of 171 pairs). For the vowel /u/ in the English group, bilabial consonants /p/ and /b/ were found to lead to significantly lower F2 than alveolar consonants /d/ and /t/ (see Figure 15).

For the Mandarin group, results of two-way RM ANOVAs performed on formant frequencies obtained from vowels in a selection of consonant contexts revealed a significant consonant effect only for vowel /u/ on F1 and for vowel /a/ on F2 (see Table 6). For vowel /u/ in the Mandarin group, post-hoc test revealed a significantly higher F1 in the context of aspirated consonants /p'/ and /t'/ than in the context of an unaspirated consonant /t/ (see Figure 16.1). For vowel /a/ in the Mandarin group, post-hoc tests revealed a significantly higher F2 in an alveolar nasal /n/ than in most other consonants (see Figure 16.2).

3.5.4 Tone Effect

For the Mandarin group, results of two-way RM ANOVAs performed on formant frequencies for vowels in one consonant (/l/) context revealed a significant tone effect on F1 for vowel /i/ and on F1 and F2 for vowel /u/ (see Table 7). For vowel /i/, post-hoc tests revealed that Tone 4 had significantly higher F1 than Tones 2 and 3. For vowel /u/, post-hoc tests revealed that Tone 4 had significantly higher F1 and F2 than all other tones and Tone 1 had a significantly higher F1 than Tones 2 and 3. As shown in Figure 17, Tone 4 (vowel space area averaged from the normal and exaggerated jaw opening data = 439,058) generally exhibited the smallest vowel space as compared to Tone 3 (566,939), Tone 2 (560,334), and Tone 1 (529,540).

3.6 Consonant Length

Results of two-way RM ANOVAs performed on C-Length averaged over all consonant contexts revealed no significant language effect but a significant task effect only for vowel /i/ (see Table 4), with the exaggerated jaw opening task (Mean = 67.7 ms, SD = 13.0) showing a longer average C-Length than the normal task (Mean = 62.9 ms, SD = 11.6).

For the English group, results of two-way RM ANOVAs performed on C-Length measures obtained from CV couplets initiated with a selection of consonants revealed a significant consonant effect for all vowels and a significant consonant-by-task interaction effect for vowel /i/ (see Table 5). As shown in Figure 18.1.1, voiced plosives /b, d/, for the English group, had a significantly shorter C-Length than their voiceless counterparts /p, t/. For vowel /i/, the exaggerated jaw opening task showed a significantly longer average C-Length than the normal task only in the /p/ consonant context (see Figure 18.1.1).

For the Mandarin group, results of two-way RM ANOVAs performed C-Length measures obtained from CV couplets initiated with a selection of consonants revealed a significant consonant effect for all vowels and a significant consonant-by-task interaction effect for vowel /a/ (see Table 6). As shown in Figure 18, unaspirated plosives /p, t/, for the Mandarin group, had a significantly shorter C-Length than their aspirated counterparts /p', t'/ regardless of vowel context. For vowel /a/, the exaggerated jaw opening task showed a significantly longer average C-Length than the normal task only in the /p', t', h, ts'/ consonant contexts. Results of two-way RM ANOVAs performed on C-Length measures in one consonant (/l/) context revealed a significant tone effect for vowels /a/ (see Table 7) and post-hoc tests revealed that Tone 4 (Mean = 83.5 ms, SD = 17.2) had a significantly longer C-Length than Tone 2 (Mean = 75.4 ms, SD = 15.6).

3.7 Summary of Main Findings

The main findings of this study are summarized as follows.

1. Language Effect: The Mandarin group was found to exhibit lower %jitter and %shimmer, higher SNR, higher OQ (for vowel /a/), lower F2 (for vowel /u/), and larger vowel space than the English group. No significant language effect was found for the extent of jaw opening, F0, SQ, or F1.
2. Task Effect: The exaggerated jaw opening task was found to result in larger extent of jaw opening, increased F0, decreased %jitter and %shimmer, increased SNR, vowel-dependent changes of F1 and F2 (i.e., lower F1 and higher F2 for vowel /i/ and higher F1 and lower F2 for vowel /a/) leading to expanded vowel space, and longer C-Length as compared with the normal task. No significant task effect was found for extent of jaw opening, OQ, or SQ.
3. Consonant Effect: For the English group, a voiceless bilabial plosives /p/ was associated with a larger extent of jaw opening and higher %shimmer than its voiced counterpart /b/ (in the context of /u/), a voiceless alveolar /t/ with a higher OQ (in the context of /i/) and lower SQ (in the context of /i/ or /u/) than its voiced counterpart /d/, bilabial plosives with a lower F2 (in the context of /a/ or /u/) than alveolar plosives, voiceless consonants with a longer C-Length (in all vowel contexts), and nasals with higher F1 than most other consonants (in the context of /a/). For the Mandarin group, aspirated consonants were associated with higher F0 (in the /i/ or /a/ context), higher OQ and lower SQ (for velar plosives in the /a/ context), higher F1 (in the /u/ context), and longer C-Length (in all vowel contexts) than their unaspirated counterparts while nasals were associated with higher F2 (in the /a/ context) and higher SNR (in the /a/ context).

4. Tone Effect: All experimental measures were affected by tone except for the extent of jaw opening, SQ, and OQ. While both Tones 1 and 4 were associated with higher F0 (in all vowel contexts) and higher F1 (in the /i/ or /u/ context) and higher F2 (in the /u/ context), Tone 1 was associated with lower %jitter and %shimmer, higher SNR, and lower SQ (in the /u/ context only) but Tone 4 showed higher %jitter and %shimmer, lower SNR, higher SQ (in the /u/ context only), and the smallest vowel space. The increase of F0 with exaggerated jaw opening was most evident in Tone 1.

Chapter 4. DISCUSSION

This study employs a multi-channel instrumental setup to conduct a cross-language and cross-system study of the impact of jaw opening on speech and voice with an attempt to understand the relationship between jaw opening and phonetic complexity. Based on the empirical data as reported in the previous section, this chapter provides a discussion of the findings in relation to the research question, previous research, clinical implication, and limitations of the study and future direction.

4.1 Related to Research Question

The research question, as previously stated, is whether and how the jaw opening approach (i.e., changes in the vocal tract configuration), which was commonly used in articulatory and voice therapy, may impact on vocal behaviors (i.e., changes in the source) as well as speech and voice quality. Specifically, it was predicted that measurable changes in articulatory and laryngeal movements could be obtained to help understand how the articulators and vocal apparatus may be adjusted in response to a variety of phonetic contexts to reduce phonetic complexity and thus to enhance speech production. The hypothesis that an exaggerated jaw opening posture has a positive impact on speech and voice production was supported with the main finding that an exaggerated jaw opening posture, as confirmed in this study with measures of the extent of jaw opening, generally resulted in a larger vowel space, which has been shown in the literature to be associated with increased speech intelligibility, and positive changes in phonatory stability, reflected in a decrease in %jitter and %shimmer and an increase in SNR. Changes in the formant frequencies as a result of an exaggerated jaw opening posture suggested that tongue positioning and vocal tract configuration were affected by the extent of jaw displacement. The demonstrated positive effect of the jaw-based global adjustment to the vocal tract configuration on speech and voice quality indicated that emphasis on jaw opening in speech production, or at least in production of monosyllabic words as shown in this study, would assist in improving phonatory stability as well as most possibly speech intelligibility. Although there was no direct auditory-perceptual judgement made in this study, the association between increased jaw opening and increased vowel space was shown for both English and Mandarin speakers, suggesting that speech produced with an increased jaw opening posture was at least beneficial for vowel differentiation. This finding supports the hypothesis that modification in jaw displacement may alter the acoustic-phonetic features critical to speech intelligibility.

As for the hypothesis that the importance of jaw displacement in speech production was due to its structural support to the tongue, it is only supported as far as vowel production is concerned because although an exaggerated jaw opening posture was indeed found to result in a positive change in vowel space or formant frequencies, which were related to tongue height and advancement, the effect of an exaggerated jaw opening posture on most experimental measures, including phonatory stability, was no more evident in apical sounds (e.g., /t, d/) than in bilabial sounds (e.g., /p, b/). This finding suggested that jaw opening had an impact on speech and voice whether or not the consonant formation involved tongue movement. In addition, assuming that consonant prolongation was advantageous to speech clarity, the present finding that an exaggerated jaw opening posture resulted in longer consonant length only in voiceless (for English) and aspirated sounds (for Mandarin) highlighted the importance of the role of the jaw in affecting the release of airstream from the oral port with an open glottis. Furthermore, as a source-tract interaction was clearly shown with the finding that an exaggerated jaw opening posture led to changes in F0 and glottal measures (i.e., OQ and SQ), the contribution of the jaw to the reduction of phonetic complexity should not be limited to articulatory movements alone and a cross-system coordination, such as oral-laryngeal coordination or the aerodynamic or resonance change in the vocal tract, should be taken into consideration when gauging the complexity of speech motor demand.

4.2 Related to Previous Research

This study yielded instrumental measures that could be compared with those in previous studies, leading to an improved understanding of the language effect on vowel space, the relationship between vowel space and speech improvement, the effect of articulatory control on phonatory stability, and the interaction between jaw displacement and phonetic context on speech acoustics, all of which may shed lights on the question as to how jaw opening may be used to assist in reducing phonetic complexity.

4.2.1 Language Effect on Vowel Space

The Mandarin group was found to exhibit a larger vowel space than the English group, mainly due to F2 lowering for the vowel /u/. The fronting of back vowels is one of the universal rules of language changes observed by Labov (1994). Watson, Harrignton, and Evans (1998), in a study of the Otago speech database including speech samples from 11 males and 10 females aged between 16 and 33 years, found that vowel fronting was one of the speech characteristics of native speakers of modern New Zealand English. This observation was supported by further studies (Gordon et al, 2004; Maclagan et al., 2005; Maclagan & Hay, 2007). Since Mandarin /u/ is not fronted, the front-shifting of New Zealand English may account for the language effect on vowel space found in this study.

4.2.2 Vowel Space and Speech Improvement

The present finding that both language groups exhibited expansion of the vowel space when using an exaggerated jaw opening posture is consistent with the finding of Smiljanić and Bradlow (2005) that the effect of "clear speech" on speech intelligibility is a universal phenomenon. In other words, vowel space expansion may be considered a universal intelligibility-enhancing strategy applicable across languages. In particular, with the simultaneous cross-system monitoring approach and the physiological measures included in this study, the present finding provided strong empirical evidences supporting the hypothesis that the hyperarticulation/jaw-opening technique would result in a positive change in vowel space and voice quality.

Smiljanić and Bradlow (2005) compared the "clear speech", defined as the speaking style in which "the talkers read as if they were talking to a listener with a hearing loss or a non-native speaker " (p. 1680), obtained from five Croatian (three males and two females, aged between 18 and 25 years) and five English speakers (two males and three females, aged between 28 and 48 years) on measures of speaking rate, pitch range, and vowel space as well as perceptual judgements from 50 adult normal-hearing listeners (20 Croatian and 30 English speakers). Smiljanić and Bradlow (2005) found that regardless of language, "clear speech" was associated with improved speech intelligibility, decreased speech rate, increased pitch range, and larger vowel space areas. Furthermore, Bradlow et al. (1996) studied the acoustic characteristics of the speech samples in a database of 2,000 sentences produced by 20 healthy American English speakers (10 males and 10 females) and found, based on the perception of 200 listeners (with speech intelligibility scores obtained from 10 listeners per speaker), that speakers with higher speech intelligibility scores were associated with larger vowel space and that vowel space was more closely related to speech intelligibility as compared with average F0 and speaking rate.

Evidence in support of the relationship between vowel space and speech intelligibility can also be found in treatment efficacy studies. The LSVT, as previously mentioned, was a speech and voice training program focusing on increasing loudness as a way to improve speech articulation, respiratory, and laryngeal functions for individuals with PD (Dromey et al., 1995; Ramig et al., 1994; Sapir et al., 2007; Solomon et al., 2001). Sapir and colleagues (2007), in a treatment efficacy study of LSVT, found that speech of post-treatment individuals with PD showed an increase in vowel space and received improved acoustic and perceptual vowel ratings, suggesting that significant formant frequency changes might indicate improvements in speech and voice. Similarly, Huber and Chandrasekaran (2006), in a study of 30 healthy nonsmokers with no formal speaking or singing training (15 males and 15 females, with a mean age of 22 years), reported that there was a significant loudness effect on F1 and F2, suggesting that changes in formant frequency were related to vocal effort. The present finding that an exaggerated jaw opening posture led to a larger vowel space as well as improved phonatory stability was in agreement with reports in previous studies of a positive relationship between vowel space and speech improvement.

4.2.3 Articulatory Control and Phonatory Stability

Although an open-mouth or jaw opening technique was not directly indicated in the type of training program involving loudness control, the emphasis on loudness increase most likely may facilitate an open-mouth posture. The effect of loudness on formant frequencies may result from either changes of laryngeal aerodynamics triggered by a change in respiratory support or changes of oral resonance due to a change in vocal tract configuration. The present finding that an exaggerated jaw opening posture resulted in a change in vocal parameters, including F0, %jitter, %shimmer, and SNR, suggested that previous findings on the positive effect of increased loudness might be partly related to the jaw opening posture, which was not monitored in previous studies and thus could not be ruled out as a contributing factor for speech and voice improvement. In other words, the jaw opening technique may not only change the spatio-temporal articulatory movement in the oral cavity but also affect the stability of laryngeal movements.

Perturbation measures have been found to be affected by intensity (Gelfer et al., 1995; Orlikoff & Kahane, 1991). In a study of 29 healthy females (aged from 20 to 27 years), Gelfer (1995) found that %jitter, %shimmer, and SNR varied by pitch, intensity, and vowel, with an increase of pitch and intensity resulting in improved phonatory stability. One speculation was that phonation at low sound pressure level, which has been found to be associated with a longer open phase of the vocal fold vibratory cycle, might be more susceptible to an increase in supraglottic pressure, laryngeal muscle tension, and air flow turbulence and thus phonatory instability. The finding from the Mandarin data in this study that the nasal /n/ tended to be associated with lower OQ and higher SNR than most other consonants supported this speculation. The finding that Tones 3 and 4 were associated with higher SQ, higher %jitter, higher %shimmer, and lower SNR than Tones 1 and 2 suggested that phonatory stability was also related to vocal fold tension, which could be reflected in SQ. It is noteworthy, however, that the positive effect of jaw opening on phonatory stability was most evident for high vowels /i/ and /u/ in this study. This finding may be related to the fact that the low vowel /a/ was already associated with an open mouth posture and thus the positive effect of jaw opening on phonatory stability was limited for this vowel. Although the positive effect of jaw opening on phonatory stability was not shown in the vowel /a/, the finding that an exaggerated jaw opening posture was associated with lower OQ and higher SQ in this vowel context for most consonants involving aspiration or frication also supports the aforementioned source-tract linkage hypothesis.

4.2.4 Jaw Displacement and Phonetic Context

The present finding regarding the interaction between jaw displacement and phonetic contexts provided evidences suggesting that the motor demand associated with different phonemes with different levels of phonetic complexity could be affected by jaw displacement. For example, the English speakers in this study exhibited a significant decrease in F2 frequency with the exaggerated jaw opening posture only when the vowel /a/ was preceded by consonants: /k/, /ʧ/, /ʤ/, and /l/ and a significant increase in C-Length only when the vowel /i/ was preceded by plosives (/p, b, t, d/). These context-dependent jaw opening effects were consistent with the observations by Steven and House (1963) in a study of three male adult American English speakers and Hillenbrand and Clark (2001) in a study of 12 healthy speakers (6 females and 6 males, aged between 25 to 64 years) with CVC speech utterances that vowel formant patterns were affected by both vowel and consonant contexts.

For English speakers, the finding in the vowel /u/ that vowel production following bilabial consonants /p/ and /b/ were associated with a lower F2 as compared with those following alveolar sounds may be related to the difference between bilabial and alveolar sounds on the degree of tongue advancement required. Since a lower F2 is indicative of a more backward tongue positioning or a greater degree of posterior oral constriction (Baken & Orlikoff, 2000), it is most likely that bilabial sounds pose less restriction than alveolar sounds on the tongue placement allowing the tongue to move more freely to a more backward position in the context of a back vowel /u/. A similar cross-system coarticulation effect has also been shown in the finding from the

Mandarin group that un-aspirated consonants tended to be associated with a lower F2 because tongue advancement is most likely to be more restricted by the laryngeal positioning posed for voicing.

Another phenomenon of coarticulation effect can be observed from the finding in the vowel /a/ for the English group that nasals /m/ and /n/ tended to be associated with a higher F1. F1 raising has been considered to correspond to a lower tongue position or a less degree of pharyngeal constriction (Baken & Orlikoff, 2000). The F1 raising in the context of nasals can be related to the physical linkage between velum (soft palate) and tongue, with lowering of the velum (to open up the velopharyngeal port to allow air to go through the nasal passage in the production of nasals) tending to result in lowering of the tongue and thus F1 raising. To illustrate this point, Table 8 was compiled according to the classic descriptions in anatomy and physiology (e.g., Dickens & Maue-Dickens, 1982; Perkins & Kent, 1986) to identify the muscle involvement for a variety of articulatory movement included in this study. As shown in Table 8, velum lowering, which was required for production of nasals, involved contraction of palatoglossus, which "extends from the anterior velum through the anterior pillar of fauces to insert into the side of the root of the tongue" (Dickens & Maue-Dickens, 1982, p. 237). Therefore, the reason why vowels produced in the context of nasals exhibited higher F1 may lie in the linkage between velum and tongue and between tongue and larynx. Likewise, mandible lowering, which was required to achieve an exaggerated jaw opening posture, involved contraction of the geniohyoid and the anterior belly of digastric, both of which insert into the hyoid bone, which may affect laryngeal positioning. These physiologically based interpretations help support the physical linkage hypothesis for a source-tract interaction, highlighting the importance of jaw positioning in oral-laryngeal coordination and in affecting the motor demands in different phonetic contexts.

The similarity on the task effect shown in this study between English and Mandarin speakers suggests that the impact of jaw opening on the reduction of phonetic complexity was universal to some extent. However, the tone effect on speech and voice measures also showed that some aspects of the jaw opening effect on speech and voice could be language-specific. For example, the oral-laryngeal coordination needed for the language-dependent prosodic control may pose different levels of phonetic complexity for speech sound production. Since Mandarin is a tonal language and tone control was associated with the vibratory pattern and the positioning of the larynx, the finding that there was a tone-by-task interaction effect on F0 and SQ suggested that the effect of jaw opening on reducing the motor demand of phonetic complexity would be affected by the phonemic usage of F0.

In summary, the impact of jaw opening on articulatory and vocal behaviours was shown to have a universal positive context-dependent effect on speech and voice as well as a language-induced difference due to the difference in the phonemic usage of vocal features in different phonological systems.

4.3 Clinical Implication

The current experiment provides cross-language as well as cross-system evidences showing the impact of jaw opening on articulatory and vocal behaviours. The rationale of the technique of an exaggerating jaw opening or a full articulation approach, also known as hyper of over-articulation, is strengthened by the present finding. The normative data provides the foundation for further investigation in support of an evidence-based practice regarding the usage of a jaw opening technique in individuals with motor speech disorders. This study provides empirical evidences confirming that the jaw plays a critical role in speech and voice enhancement and thus suggesting that jaw manipulation through other facilitating or assistive devices may be considered. Since the exaggerated jaw opening technique has been shown to improve speech intelligibility for individuals with dysarthria (Freed, 2000) and voice treatment suggestive of an open-mouth approach has been shown to improve intensity and voice quality (Dromey et al., 1995; Ramig et al., 1994; Sapir et al., 2007; Solomon et al., 2001), the present finding of a positive jaw opening effect on speech and voice production suggests that development of a prosthetic mandibular support device may be a feasible alternative or assistive option for enhancing the speech of individuals with speech motor disorders.

4.4 Limitations of the Study and Future Direction

The impact of jaw opening on articulatory and vocal behaviours was investigated in this study through observations on monosyllabic CV couplets produced by 20 participants. Despite findings of a positive effect of jaw opening on speech and voice, there are some limitations. In particular, although the unique multichannel recording device employed in this study not only has the advantage of enhancing the efficiency of data collection but also allows for simultaneous cross-system observations of the speech production behaviors, the marker-based facial tracking device posed some challenges to data collection due to the effect of the contour of the face on the placement of the reflective materials. The markers placed on the two sides of the lips were sometimes hard to trace when they moved out of the covering range of the infrared light source, especially during speech production involving lip rounding (e.g., production of the vowel /u/). This instrumental limitation has slowed down some of the data collection process and thus limiting the range of speech samples as well as resulting in missing data, which may weaken the validity of the observations made from the facial tracking data. Further modification on the facial tracking software is underway to improve the success rate of data collection.

In addition, since speech movement is dynamic, involving a series of complex coordinative gestures, the generalization of the present findings can be improved at least in two aspects. Firstly, samples from multisyllabic speech samples as well as connective speech are still needed for better generalization of the present findings to natural speech. Secondly, as voice quality measures were found to be related to F0 and some intersubject variations could be observed from analyses of individual data, a greater sample size is needed to allow for study of the effect of age as well as gender.

4.5 Conclusion

The current study provides empirical evidences in support of a positive effect of jaw opening on speech and voice, suggesting an effect of jaw opening on reducing phonetic complexity. An increase in jaw opening was found to result in improved phonatory stability and vowel space, as well as showing an interaction with phonetic context on the induced changes in various speech and voice measures. A language-specific jaw effect was also demonstrated in the speech samples obtained from tonal language users.

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Table 1. Place and manner of articulation for English (E) and Mandarin (M) phonemes transcribed in International Phonetic Alphabet (symbols in parentheses are the phonetic symbols commonly used in Taiwan).

	Bilabial		Interdental		Labiodental		Alveolar		Palatal		Velar		Glottal	
	E	M	E	M	E	M	E	M	E	M	E	M	E	M
Plosive	p	p' (ㄆ)					t	t' (ㄊ)			k	k' (ㄎ)		
	b	p (ㄅ)					d	t (ㄉ)			g	k (ㄍ)		
Fricative			θ		f	f (ㄈ)	s	s (ㄙ)	ʃ	ɕ (ㄒ) ʂ (ㄕ)			h	h (ㄏ)
			ð		v		z		ʒ					
Affricate								ts' (ㄘ)	tʃ	tɕ' (ㄑ) tʂ' (ㄔ)				
								ts (ㄗ)	ʤ	tɕ (ㄐ) tʂ (ㄓ)				
Lateral							l	l (ㄌ)						
Nasal	m	m (ㄇ)					n	n (ㄋ)						
Retroflex							r	r (ㄖ)						

Table 2. Ranking the phonetic complexity of 19 English consonants.

Consonant	Individual Rank Score			Composite Score	
	Phonetic Product	Manner of Articulation	Development	Total Scores	Rank
m	3	1	1	5	1
k	2	2	2	6	2
h	2	3	1	6	2
p	3	2	1	6	2
g	2	2	2	6	2
b	3	2	1	6	2
n	5	1	1	7	3
ʃ	1	3	5	9	4
t	5	2	2	9	4
d	5	2	2	9	4
ʧ	1	4	5	10	5
f	4	3	3	10	5
ʤ	1	4	6	11	6
s	5	3	4	12	7
v	4	3	6	13	8
z	5	3	5	13	8
l	5	5	4	14	9
θ	5	3	7	15	10
ð	5	3	8	16	11

Source:
Phonetic product (pp) ranking: Bauer (1988); Carterette and Jones (1974)
Developmental ranking (manner of articulation): Prather et al. (1975); Stoel-Gammon (1985)
Developmental ranking (speech acquisition): Sander (1972, p. 62)

Table 3. Ranking the phonetic complexity of 17 Mandarin consonants.

Consonant		Individual Rank Score			Composite Score	
		Phonetic Product	Manner of Articulation	Development	Total Scores	Rank
m	ㄇ	3	1	1	5	1
p’	ㄆ	3	2	1	6	2
p	ㄅ	3	2	1	6	2
h	ㄏ	2	3	1	6	2
k’	ㄎ	2	2	2	6	2
k	ㄍ	2	2	2	6	2
n	ㄋ	5	1	1	7	3
t’	ㄊ	5	2	2	9	4
t	ㄉ	5	2	2	9	4
f	ㄈ	4	3	3	10	5
s	ㄙ	5	3	4	12	6
ts’	ㄘ	5	4	5	14	7
ts	ㄗ	5	4	5	14	7
l	ㄌ	5	5	4	14	7
ʂ	ㄕ	6	3	5	14	7
tʂ’	ㄔ	6	4	5	15	8
tʂ	ㄓ	6	4	9	19	9

Source:
Phonetic product (pp) ranking: Bauer (1988); Carterette and Jones (1974)
Developmental ranking (manner of articulation): Prather et al. (1975); Stoel-Gammon (1985)
Developmental ranking (speech acquisition): Sander (1972, p. 62)

Table 4. Two-way (language by task) RM ANOVA results for both language groups on all experimental measures for the vowels /i/, /a/, and /u/ respectively.

	N	Language Effect	Task Effect	Language x Task Interaction Effect
/i/				
Jaw	38[†]	$F(1, 17) = 1.067, p = 0.316$	$F(1, 17) = 22.48, p < 0.001$**	$F(1, 17) = 0.242, p = 0.629$
F1	40	$F(1, 18) = 4.117, p = 0.058$	$F(1, 18) = 6.184, p = 0.023$*	$F(1, 18) = 1.130, p = 0.302$
F2	40	$F(1, 18) = 0.008, p = 0.930$	$F(1, 18) = 6.960, p = 0.017$*	$F(1, 18) = 13.32, p = 0.002$**
F0	40	$F(1, 18) = 0.938, p = 0.346$	$F(1, 18) = 4.700, p = 0.044$*	$F(1, 18) = 0.057, p = 0.814$
%jitter	40	$F(1, 18) = 15.84, p < 0.001$**	$F(1, 18) = 13.68, p = 0.002$**	$F(1, 18) = 0.725, p = 0.406$
%shimmer	40	$F(1, 18) = 4.236, p = 0.054$	$F(1, 18) = 16.44, p < 0.001$**	$F(1, 18) = 0.753, p = 0.397$
SNR	40	$F(1, 18) = 12.21, p = 0.003$**	$F(1, 18) = 6.490, p = 0.020$*	$F(1, 18) = 0.058, p = 0.813$
SQ90	40	$F(1, 18) = 0.817, p = 0.378$	$F(1, 18) = 2.174, p = 0.158$	$F(1, 18) = 1.754, p = 0.202$
OQ90	40	$F(1, 18) = 0.651, p = 0.430$	$F(1, 18) = 0.350, p = 0.561$	$F(1, 18) = 0.475, p = 0.499$
C-Length	40	$F(1, 18) = 1.633, p = 0.217$	$F(1, 18) = 4.711, p = 0.044$*	$F(1, 18) = 0.050, p = 0.826$
/a/				
Jaw	38[†]	$F(1, 17) = 0.203, p = 0.658$	$F(1, 17) = 70.41, p < 0.001$**	$F(1, 17) = 0.289, p = 0.598$
F1	40	$F(1, 18) = 1.543, p = 0.230$	$F(1, 18) = 43.13, p < 0.001$**	$F(1, 18) = 3.234, p = 0.089$
F2	40	$F(1, 18) = 0.390, p = 0.540$	$F(1, 18) = 5.107, p = 0.036$*	$F(1, 18) = 1.767, p = 0.200$
F0	40	$F(1, 18) = 0.830, p = 0.374$	$F(1, 18) = 10.01, p = 0.005$**	$F(1, 18) = 0.010, p = 0.920$
%jitter	40	$F(1, 18) = 15.11, p < 0.001$**	$F(1, 18) = 0.968, p = 0.338$	$F(1, 18) = 1.265, p = 0.275$
%shimmer	40	$F(1, 18) = 8.469, p = 0.009$**	$F(1, 18) = 3.583, p = 0.075$	$F(1, 18) = 1.074, p = 0.314$
SNR	40	$F(1, 18) = 5.105, p = 0.036$*	$F(1, 18) = 0.019, p = 0.891$	$F(1, 18) = 6.646, p = 0.019$*
SQ90	39[†]	$F(1, 18) = 3.833, p = 0.066$	$F(1, 17) = 1.709, p = 0.208$	$F(1, 17) = 1.337, p = 0.263$
OQ90	39[†]	$F(1, 18) = 5.042, p = 0.037$*	$F(1, 17) = 2.613, p = 0.124$	$F(1, 17) = 0.688, p = 0.418$
C-Length	40	$F(1, 18) = 0.755, p = 0.396$	$F(1, 18) = 4.294, p = 0.053$	$F(1, 18) = 0.345, p = 0.564$
/u/				
Jaw	38[†]	$F(1, 17) = 0.150, p = 0.703$	$F(1, 17) = 9.523, p = 0.007$*	$F(1, 17) = 0.840, p = 0.372$
F1	40	$F(1, 18) = 1.558, p = 0.228$	$F(1, 18) = 2.379, p = 0.140$	$F(1, 18) = 0.795, p = 0.384$
F2	40	$F(1, 18) = 80.94, p < 0.001$**	$F(1, 18) = 4.051, p = 0.059$	$F(1, 18) = 0.005, p = 0.943$
F0	40	$F(1, 18) = 0.692, p = 0.416$	$F(1, 18) = 9.574, p = 0.006$**	$F(1, 18) = 1.212, p = 0.285$
%jitter	40	$F(1, 18) = 14.91, p = 0.001$**	$F(1, 18) = 10.85, p = 0.004$**	$F(1, 18) = 5.756, p = 0.027$*
%shimmer	40	$F(1, 18) = 2.213, p = 0.154$	$F(1, 18) = 11.79, p = 0.003$**	$F(1, 18) = 0.247, p = 0.625$
SNR	40	$F(1, 18) = 6.396, p = 0.021$*	$F(1, 18) = 23.14, p < 0.001$**	$F(1, 18) = 6.164, p = 0.023$*
SQ90	40	$F(1, 18) = 1.712, p = 0.207$	$F(1, 18) = 2.810, p = 0.111$	$F(1, 18) = 3.583, p = 0.075$
OQ90	40	$F(1, 18) = 3.471, p = 0.079$	$F(1, 18) = 2.356, p = 0.142$	$F(1, 18) = 1.304, p = 0.268$
C-Length	40	$F(1, 18) = 1.062, p = 0.316$	$F(1, 18) = 1.781, p = 0.199$	$F(1, 18) = 0.0004, p = 0.984$

* Significant at 0.05 level
**Significant at 0.005 level
[†]Missing data

Table 5. Two-way (consonant by task) RM ANOVA results for the English group on all experimental measures for vowels /i/, /a/, and /u/ respectively.

	N	Consonant Effect	Task Effect	Consonant x Task Interaction Effect
/i/				
Jaw	80	F(3, 27) = 1.816, p = 0.168	F(1, 9) = 18.90, p = 0.002**	F(3, 27) = 0.393, p = 0.759
F1	80	F(3, 27) = 0.539, p = 0.660	F(1, 9) = 6.087, p = 0.036*	F(3, 27) = 0.037, p = 0.990
F2	80	F(3, 27) = 0.846, p = 0.481	F(1, 9) = 21.14, p = 0.001**	F(3, 27) = 0.109, p = 0.594
F0	80	F(3, 27) = 2.369, p = 0.093	F(1, 9) = 1.492, p = 0.253	F(3, 27) = 0.035, p = 0.991
%jitter	80	F(3, 27) = 1.741, p = 0.182	F(1, 9) = 9.018, p = 0.015*	F(3, 27) = 0.819, p = 0.495
%shimmer	80	F(3, 27) = 0.368, p = 0.777	F(1, 9) = 7.126, p = 0.026*	F(3, 27) = 0.447, p = 0.722
SNR	80	F(3, 27) = 0.315, p = 0.814	F(1, 9) = 3.175, p = 0.108	F(3, 27) = 2.234, p = 0.107
SQ90	80	F(3, 27) = 5.531, p = 0.004**	F(1, 9) = 4.253, p = 0.069	F(3, 27) = 1.630, p = 0.206
OQ90	80	F(3, 27) = 5.769, p = 0.003**	F(1, 9) = 2.211, p = 0.171	F(3, 27) = 1.151, p = 0.346
C-Length	80	F(3, 27) = 85.67, p < 0.001**	F(1, 9) = 2.378, p = 0.157	F(3, 27) = 3.388, p = 0.032*
/a/				
Jaw	378†	F(18, 162) = 0.998, p = 0.465	F(1, 9) = 54.34, p < 0.001**	F(18, 160) = 1.19, p = 0.277
F1	378†	F(18, 162) = 3.771, p < 0.001**	F(1, 9) =16.23, p = 0.003**	F(18,160) = 0.889, p = 0.592
F2	378†	F(18, 162) = 8.166, p < 0.001**	F(1, 9) =2.399, p = 0.156	F(18,160) = 1.870, p = 0.022*
F0	378†	F(18, 162) =1.173, p = 0.290	F(1, 9) =1.433, p =0.262	F(18,160) = 0.660, p = 0.846
%jitter	378†	F(18, 162) = 1.292, p = 0.199	F(1, 9) = 1.085, p = 0.325	F(18, 160) = 0.417, p = 0.983
%shimmer	378†	F(18, 162) = 1.146, p = 0.313	F(1, 9) = 3.340, p = 0.101	F(18, 160) = 0.632, p = 0.870
SNR	378†	F(18, 162) = 1.370, p = 0.153	F(1, 9) = 0.823, p = 0.388	F(18, 160) = 0.444, p = 0.976
SQ90	210†	F(18, 90) = 1.0050, p = 0.461	F(1, 5) =1.651, p = 0.241	F(18, 72) = 0.9010, p = 0.579
OQ90	210†	F(18, 90) = 0.7170, p = 0.786	F(1, 5) = 0.006, p = 0.939	F(18, 72) = 0.6830, p = 0.817
C-Length	378†	F(18, 162) = 26.48, p < 0.001**	F(1, 9) = 0.007, p = 0.933	F(18, 160) = 0.719, p = 0.788
/u/				
Jaw	79†	F(3, 27) = 7.235, p < 0.001**	F(1, 9) = 13.57, p = 0.005**	F(3, 26) = 1.940, p = 0.148
F1	80	F(3, 27) = 3.067, p = 0.045*	F(1, 9) = 2.249, p = 0.168	F(3, 27) = 0.348, p = 0.791
F2	80	F(3, 27) = 12.03, p < 0.001**	F(1, 9) = 1.064, p = 0.329	F(3, 27) = 1.424, p = 0.258
F0	80	F(3, 27) = 1.452, p = 0.250	F(1, 9) = 4.740, p = 0.057	F(3, 27) = 0.801, p = 0.504
%jitter	80	F(3, 27) = 3.686, p = 0.024*	F(1, 9) = 8.780, p = 0.016*	F(3, 27) = 1.642, p = 0.203
%shimmer	80	F(3, 27) = 3.799, p = 0.022*	F(1, 9) = 5.192, p = 0.049*	F(3, 27) = 0.846, p = 0.481
SNR	80	F(3, 27) = 0.850, p = 0.479	F(1, 9) = 28.60, p < 0.001**	F(3, 27) = 0.156, p = 0.925
SQ90	80	F(3, 27) = 3.009, p = 0.048*	F(1, 9) = 0.824, p = 0.388	F(3, 27) = 0.476, p = 0.701
OQ90	80	F(3, 27) = 1.749, p = 0.181	F(1, 9) = 0.469, p = 0.510	F(3, 27) = 0.441, p = 0.726
C-Length	80	F(3, 27) = 40.33, p < 0.001**	F(1, 9) = 1.050, p = 0.332	F(3,27) = 1.332, p = 0.285

* Significant at 0.05 level
**Significant at 0.005 level
†Missing data

Table 6. Two-way (consonant by task) RM ANOVA results for the Mandarin group on all experimental measures for vowels /i/, /a/, and /u/ respectively.

	N	Consonant Effect	Task Effect	Consonant x Task Interaction Effect
/i/				
Jaw	89†	$F(4, 32) = 2.804, p = 0.042$*	$F(1, 8) = 6.699, p = 0.032$*	$F(4, 32) = 0.417, p = 0.795$
F1	100	$F(4, 36) = 1.167, p = 0.342$	$F(1, 9) = 1.038, p = 0.335$	$F(4, 36) = 0.638, p = 0.639$
F2	100	$F(4, 36) = 1.622, p = 0.190$	$F(1, 9) = 0.487, p = 0.503$	$F(4, 36) = 0.520, p = 0.722$
F0	100	$F(4, 36) = 4.602, p = 0.004$**	$F(1, 9) = 31.98, p <0.001$**	$F(4, 36) = 3.871, p = 0.010$*
%jitter	100	$F(4, 36) = 0.193, p = 0.941$	$F(1, 9) = 4.737, p = 0.058$	$F(4, 36) = 1.236, p = 0.313$
%shimmer	100	$F(4, 36) = 0.374, p = 0.825$	$F(1, 9) = 9.414, p = 0.013$*	$F(4, 36) = 1.088, p = 0.377$
SNR	100	$F(4, 36) = 0.647, p = 0.632$	$F(1, 9) = 3.238, p = 0.105$	$F(4, 36) = 1.139, p = 0.354$
SQ90	100	$F(4, 36) = 0.940, p = 0.452$	$F(1, 9) = 0.162, p = 0.697$	$F(4, 36) = 1.635, p = 0.187$
OQ90	100	$F(4, 36) = 0.915, p = 0.466$	$F(1, 9) = 0.113, p = 0.744$	$F(4, 36) = 1.180, p = 0.336$
C-Length	100	$F(4, 36) = 68.23, p < 0.001$**	$F(1, 9) = 3.434, p = 0.097$	$F(4, 36) = 2.271, p = 0.081$
/a/				
Jaw	301†	$F(16, 128) = 2.012, p = 0.017$*	$F(1, 8) = 27.42, p = 0.001$**	$F(16, 124) = 0.825, p = 0.656$
F1	340	$F(16, 144) = 1.651, p = 0.063$	$F(1, 9) = 11.17, p = 0.009$**	$F(16, 144) = 0.996, p = 0.465$
F2	340	$F(16, 144) = 6.576, p < 0.001$**	$F(1, 9) = 1.289, p = 0.286$	$F(16, 144) = 0.300, p = 0.996$
F0	340	$F(16, 144) = 4.707, p < 0.001$**	$F(1, 9) = 4.677, p = 0.059$	$F(16, 144) = 2.030, p = 0.015$*
%jitter	340	$F(16, 144) = 1.164, p = 0.304$	$F(1, 9) = 0.317, p = 0.587$	$F(16, 144) = 1.000, p = 0.460$
%shimmer	340	$F(16, 144) = 1.772, p = 0.040$*	$F(1, 9) = 2.474, p = 0.150$	$F(16, 144) = 0.788, p = 0.697$
SNR	340	$F(16, 144) = 2.530, p = 0.002$**	$F(1, 9) = 3.795, p = 0.083$	$F(16, 144) = 1.156, p = 0.311$
SQ90	301†	$F(16, 128) = 2.616, p = 0.001$**	$F(1, 8) = 2.935, p = 0.125$	$F(16, 123) = 2.064, p = 0.014$*
OQ90	301†	$F(16, 128) = 1.963, p = 0.020$*	$F(1, 8) = 1.026, p = 0.341$	$F(16, 123) = 1.789, p = 0.040$*
C-Length	340	$F(16, 144) = 56.619, p < 0.001$**	$F(1, 9) = 1.348, p = 0.275$	$F(16, 144) = 4.036, p < 0.001$**
/u/				
Jaw	86†	$F(4, 32) = 0.667, p = 0.620$	$F(1, 8) = 0.899, p = 0.371$	$F(4, 28) = 1.948, p = 0.130$
F1	100	$F(4, 36) = 3.774, p = 0.012$*	$F(1, 9) = 0.305, p = 0.594$	$F(4, 36) = 1.187, p = 0.333$
F2	100	$F(4, 36) = 1.893, p = 0.133$	$F(1, 9) = 10.17, p = 0.011$*	$F(4, 36) = 1.302, p = 0.288$
F0	100	$F(4, 36) = 1.984, p = 0.118$	$F(1, 9) = 15.82, p = 0.003$**	$F(4, 36) = 0.452, p = 0.770$
%jitter	100	$F(4, 36) = 0.166, p = 0.954$	$F(1, 9) = 5.726, p = 0.040$*	$F(4, 36) = 0.697, p = 0.599$
%shimmer	100	$F(4, 36) = 0.397, p = 0.809$	$F(1, 9) = 8.865, p = 0.016$*	$F(4, 36) = 2.064, p = 0.106$
SNR	100	$F(4, 36) = 0.401, p = 0.807$	$F(1, 9) = 2.612, p = 0.140$	$F(4, 36) = 1.554, p = 0.208$
SQ90	100	$F(4, 36) = 2.878, p = 0.036$*	$F(1, 9) = 0.092, p = 0.768$	$F(4, 36) = 0.706, p = 0.593$
OQ90	100	$F(4, 36) = 1.784, p = 0.154$	$F(1, 9) = 0.449, p = 0.520$	$F(4, 36) = 0.702, p = 0.596$
C-Length	100	$F(4, 36) = 59.47, p < 0.001$**	$F(1, 9) = 0.911, p = 0.365$	$F(4, 36) = 0.923, p = 0.462$

* Significant at 0.05 level
**Significant at 0.005 level
†Missing data

Table 7. Two-way (tone by task) RM ANOVA results for the Mandarin group on all experimental measures for vowels /i/, /a/, and /u/ respectively.

	N	Tone Effect	Task Effect	Tone x Task Interaction Effect
/i/				
Jaw	72†	$F(3, 24) = 2.468, p = 0.086$	$F(1, 8) = 17.04, p = 0.003$**	$F(3, 24) = 1.347, p = 0.283$
F1	80	$F(3, 27) = 3.853, p = 0.020$*	$F(1, 9) = 3.383, p = 0.099$	$F(3, 27) = 0.463, p = 0.711$
F2	80	$F(3, 27) = 2.054, p = 0.130$	$F(1, 9) = 2.371, p = 0.158$	$F(3, 27) = 0.106, p = 0.956$
F0	80	$F(3, 27) = 46.44, p < 0.001$**	$F(1, 9) = 5.386, p = 0.045$*	$F(3, 27) = 3.476, p = 0.030$*
%jitter	80	$F(3, 27) = 11.48, p < 0.001$**	$F(1, 9) = 1.723, p = 0.222$	$F(3, 27) = 0.952, p = 0.429$
%shimmer	80	$F(3, 27) = 5.923, p = 0.003$**	$F(1, 9) = 2.594, p = 0.142$	$F(3, 27) = 0.217, p = 0.883$
SNR	80	$F(3, 27) = 17.82, p < 0.001$**	$F(1, 9) = 2.010, p = 0.190$	$F(3, 27) = 0.098, p = 0.961$
SQ90	80	$F(3, 27) = 0.951, p = 0.430$	$F(1, 9) = 1.382, p = 0.270$	$F(3, 27) = 0.144, p = 0.932$
OQ90	80	$F(3, 27) = 0.378, p = 0.770$	$F(1, 9) = 2.407, p = 0.155$	$F(3, 27) = 0.220, p = 0.882$
C-Length	80	$F(3, 27) = 1.027, p = 0.396$	$F(1, 9) = 0.226, p = 0.646$	$F(3, 27) = 2.835, p = 0.057$
/a/				
Jaw	72†	$F(3, 24) = 3.192, p = 0.042$*	$F(1, 8) = 16.96, p = 0.003$**	$F(3, 24) = 0.387, p = 0.764$
F1	80	$F(3, 27) = 1.219, p = 0.322$	$F(1, 9) = 10.41, p = 0.010$*	$F(3, 27) = 0.464, p = 0.710$
F2	80	$F(3, 27) = 2.034, p = 0.133$	$F(1, 9) = 0.009, p = 0.926$	$F(3, 27) = 1.061, p = 0.382$
F0	80	$F(3, 27) = 39.94, p < 0.001$**	$F(1, 9) = 0.106, p = 0.753$	$F(3, 27) = 1.207, p = 0.326$
%jitter	80	$F(3, 27) = 10.35, p < 0.001$**	$F(1, 9) = 0.231, p = 0.642$	$F(3, 27) = 1.960, p = 0.144$
%shimmer	80	$F(3, 27) = 6.515, p = 0.002$**	$F(1, 9) = 2.497, p = 0.149$	$F(3, 27) = 0.202, p = 0.894$
SNR	80	$F(3, 27) = 19.66, p < 0.001$**	$F(1, 9) = 4.259, p = 0.069$	$F(3, 27) = 1.502, p = 0.236$
SQ90	80	$F(3, 27) = 2.584, p = 0.074$	$F(1, 9) = 0.528, p = 0.486$	$F(3, 27) = 1.189, p = 0.333$
OQ90	80	$F(3, 27) = 2.935, p = 0.051$	$F(1, 9) = 0.00002, p = 0.996$	$F(3, 27) = 1.216, p = 0.323$
C-Length	80	$F(3, 27) = 3.066, p = 0.045$*	$F(1, 9) = 2.019, p = 0.189$	$F(3, 27) = 0.914, p = 0.447$
/u/				
Jaw	66†	$F(3, 21) = 2.633, p = 0.076$	$F(1, 7) = 19.92, p = 0.003$**	$F(3, 18) = 1.539, p = 0.239$
F1	80	$F(3, 27) = 21.94, p < 0.001$**	$F(1, 9) = 0.0002, p = 0.988$	$F(3, 27) = 0.417, p = 0.742$
F2	80	$F(3, 27) = 17.63, p < 0.001$**	$F(1, 9) = 10.99, p = 0.009$**	$F(3, 27) = 0.289, p = 0.833$
F0	80	$F(3, 27) = 57.03, p < 0.001$**	$F(1, 9) = 18.23, p = 0.002$**	$F(3, 27) = 3.188, p = 0.040$*
%jitter	80	$F(3, 27) = 12.46, p < 0.001$**	$F(1, 9) = 11.13, p = 0.009$**	$F(3, 27) = 2.745, p = 0.062$
%shimmer	80	$F(3, 27) = 6.506, p = 0.002$**	$F(1, 9) = 8.025, p = 0.020$*	$F(3, 27) = 2.094, p = 0.124$
SNR	80	$F(3, 27) = 14.34, p < 0.001$**	$F(1, 9) = 6.174, p = 0.035$*	$F(3, 27) = 0.676, p = 0.574$
SQ90	80	$F(3, 27) = 3.368, p = 0.033$*	$F(1, 9) = 0.038, p = 0.850$	$F(3, 27) = 3.618, p = 0.026$*
OQ90	80	$F(3, 27) = 2.862, p = 0.055$	$F(1, 9) = 0.131, p = 0.725$	$F(3, 27) = 2.421, p = 0.088$
C-Length	80	$F(3, 27) = 1.884, p = 0.156$	$F(1, 9) = 0.432, p = 0.527$	$F(3, 27) = 0.742, p = 0.537$

* Significant at 0.05 level
**Significant at 0.005 level
†Missing data

Table 8. Muscles involved in speech articulation.

Action	Examples of Target	Muscles that need to contract	Muscles that need to relax
Lowering the mandible	-Exaggerated jaw opening	-Lateral pterygoid -Geniohyoid -Anterior belly of digastric	-Temporalis -Masseter -Medial pterygoid
Lowering the backside of the tongue	-Low back vowel (/a/)	-Hyoglossus	-Palatoglossus
Drawing the tongue backward and upward	-High back vowel (/u/) -Velar (/k/)	-Styloglossus	-Hyoglossus
Raising the tongue tip and sides	-Alveolar (/t/)	-Superior longitudinal	-Inferior longitudinal
Lowering the velum	-Nasals (/m/, /n/)	-Palatopharyngeus -Palatoglossus	-Levator palatini

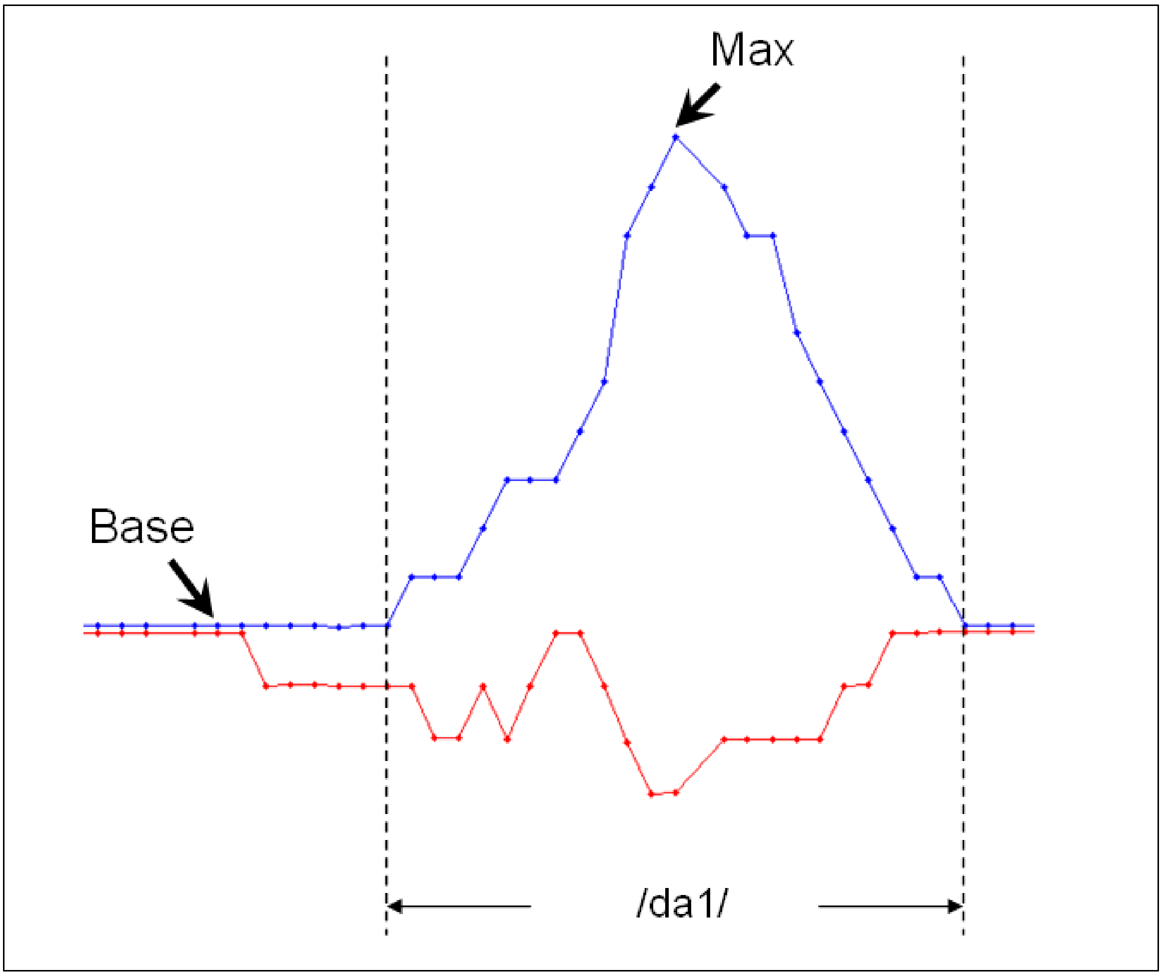


Figure 1. An illustration of the tracings of the extent of lip spreading (lower line) and jaw opening (upper line) for a male Mandarin speaker's production of /da/ at Tone 1. (The arrow labelled as "Base" marks the baseline level of the jaw at rest preceding the production and the arrow labelled as "Max" marks the maximum displacement of the jaw during production of the CV couplet.)

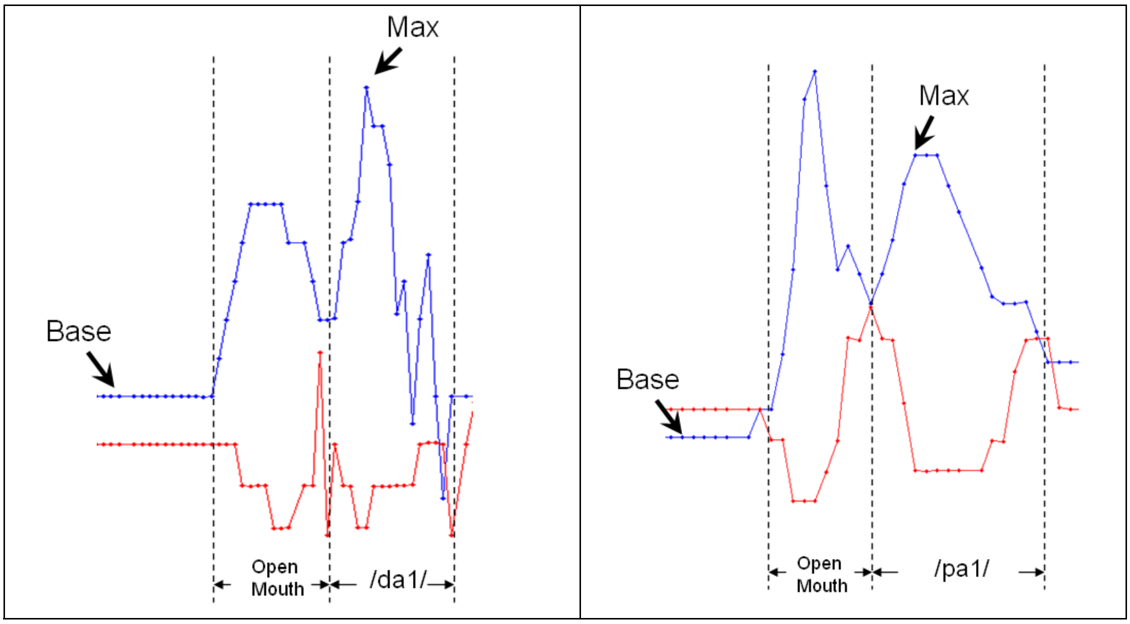


Figure 2. An illustration of the tracings of the extent of lip spreading (lower line) and jaw opening (upper line) for a male Mandarin speaker's production of /da/ (of the left) and /pa/ (on the right) at Tone 1, with a pre-phonatory mouth opening gesture shown to precede the production. (The arrow labelled as "Base" marks the baseline level of the jaw at rest preceding the production and the arrow labelled as "Max" marks the maximum displacement of the jaw during production of the CV couplet.)

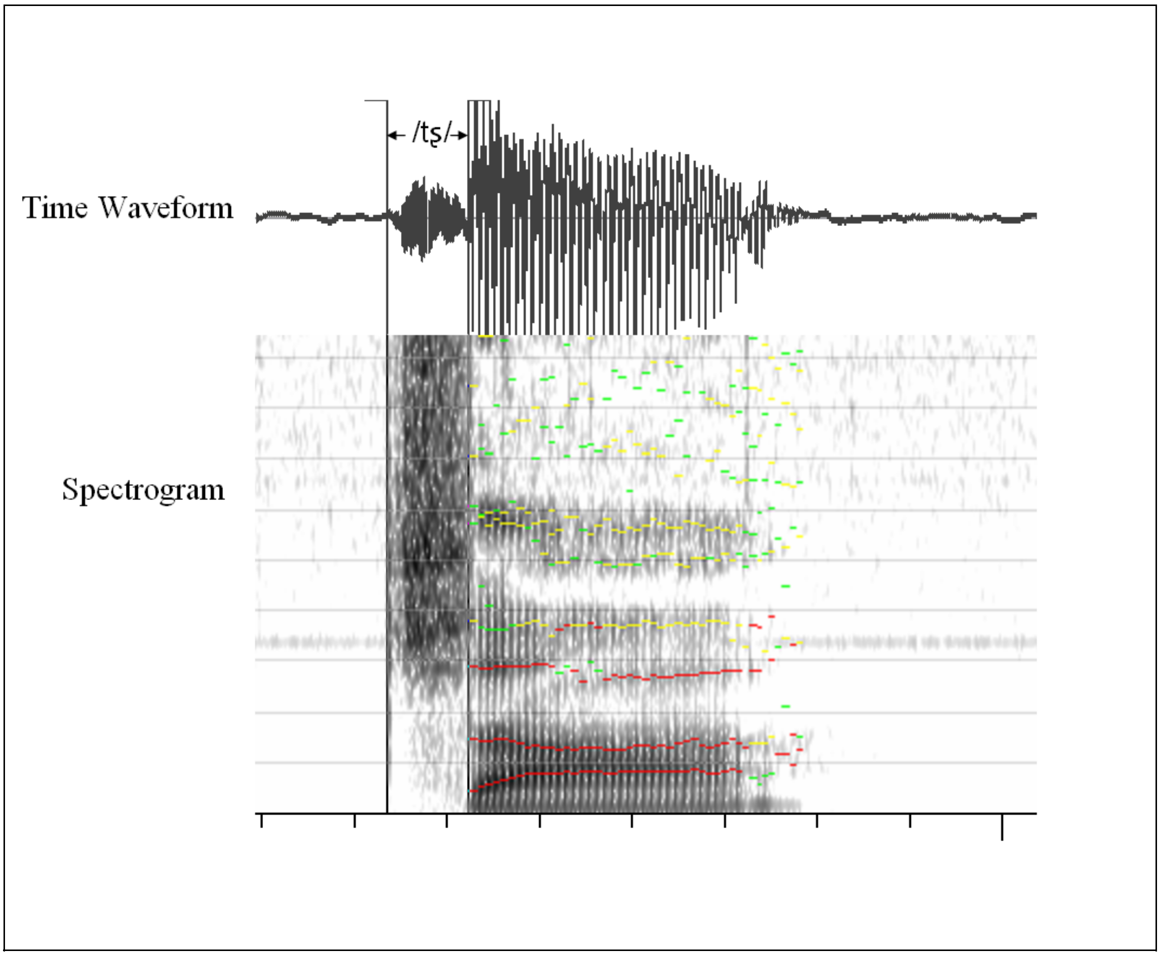


Figure 3. A display of the time waveforms and spectrogram of a male Mandarin speaker's production of /tʂa/ (ㄓㄚ), showing the cursors used to define the consonant length.

Fig. 4.1.1 /i/ - F0

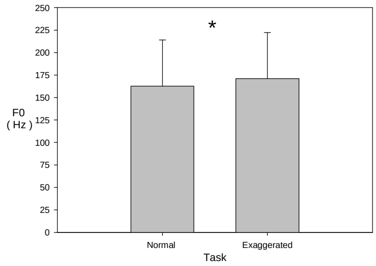


Fig. 4.1.2 /a/ - F0

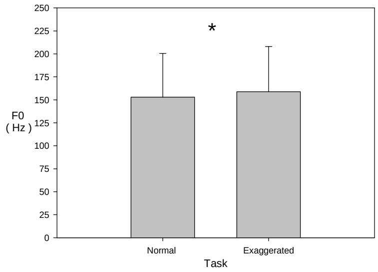


Fig. 4.1.3 /u/ - F0

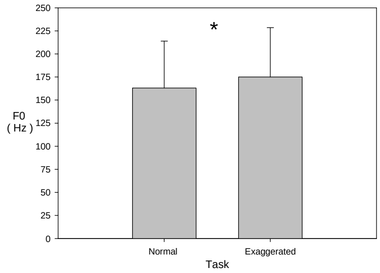


Fig. 4.2.1 /i/ - %jitter

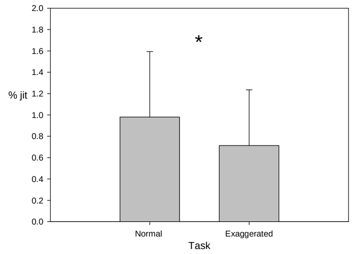


Fig. 4.2.2 /a/ - %jitter

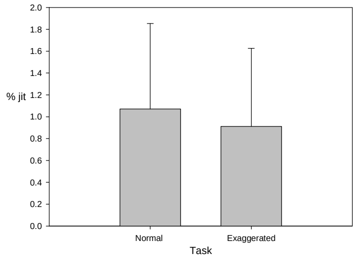


Fig. 4.2.3 /u/ - %jitter

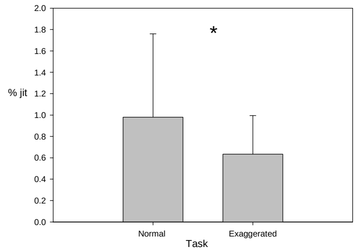


Fig. 4.3.1 /i/ - %shimmer

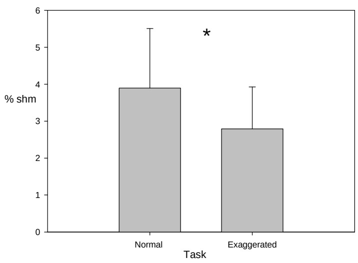


Fig. 4.3.2 /a/ - %shimmer

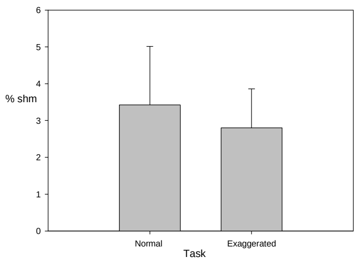


Fig. 4.3.3 /u/ - %shimmer

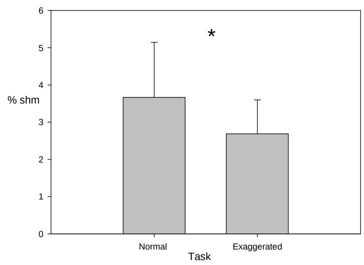


Fig. 4.4.1 /i/ - SNR

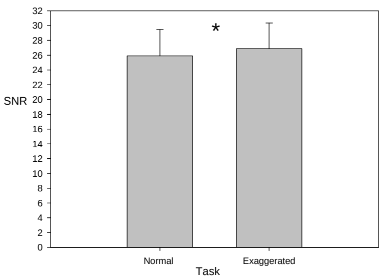


Fig. 4.4.2 /a/ - SNR

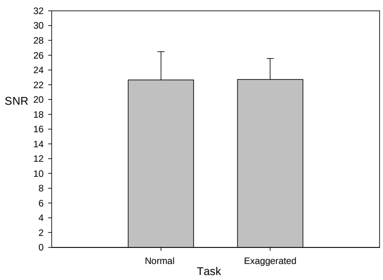


Fig. 4.4.3 /u/ - SNR

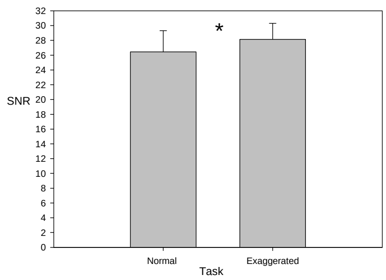


Figure 4. Task effect on F0, %jitter, %shimmer, and SNR with data from both language groups combined. (Significantly different pairs were marked with "*".)

Fig. 5.1.1 /i/ - F0

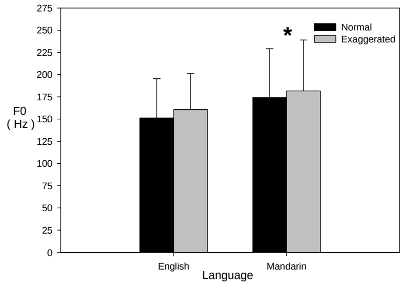


Fig. 5.1.2 /a/ - F0

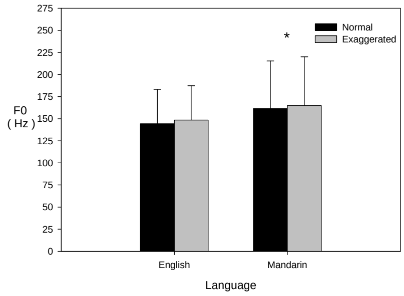


Fig. 5.1.3 /u/ - F0

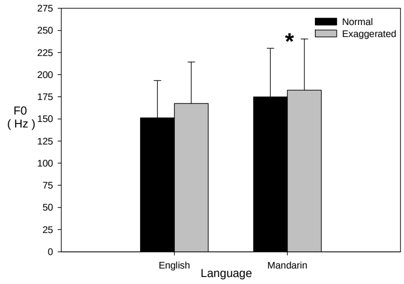


Fig. 5.2.1 /i/ - %jitter

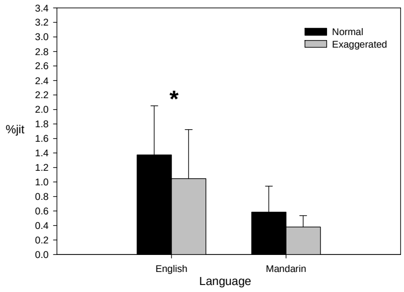


Fig. 5.2.2. /a/ - %jitter

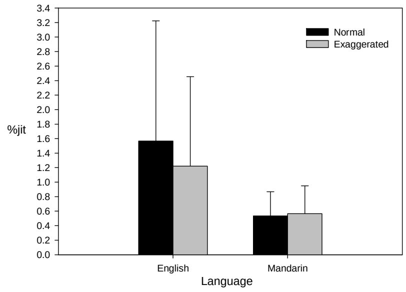


Fig. 5.2.3 /u/ - %jitter

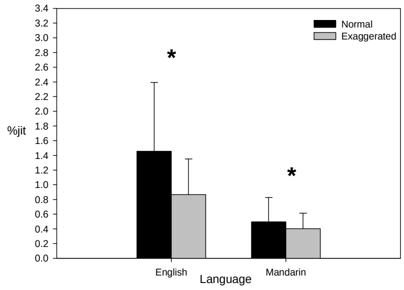


Fig. 5.3.1 /i/ - %shimmer

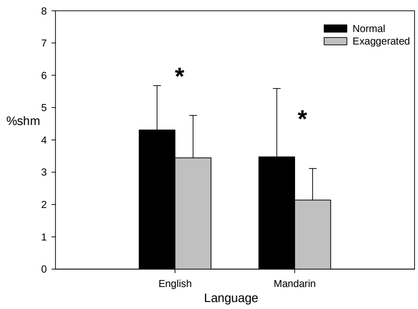


Fig. 5.3.2 /a/ - %shimmer

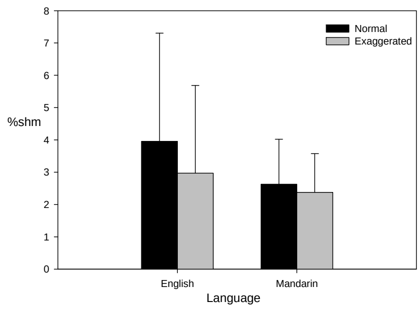


Fig. 5.3.3 /u/ - %Shimmer

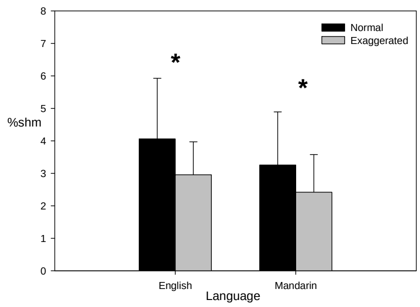


Fig. 5.4.1 /i/ - SNR

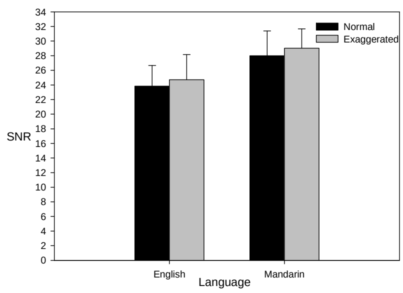


Fig. 5.4.2 /a/ - SNR

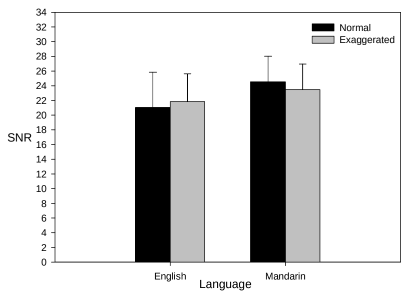


Fig. 5.4.3 /u/ - SNR

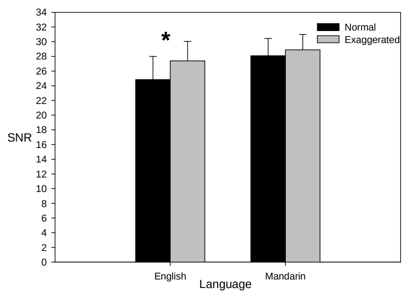


Figure 5. Task effect on F0, %jitter, %shimmer, and SNR for the English and Mandarin groups in vowels /i/, /a/, and /u/ separately. (Significantly different pairs were marked with "*".)

Fig. 6.1.1 /i/ F0

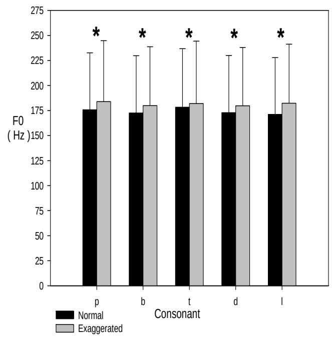


Fig. 6.1.2 /a/ F0

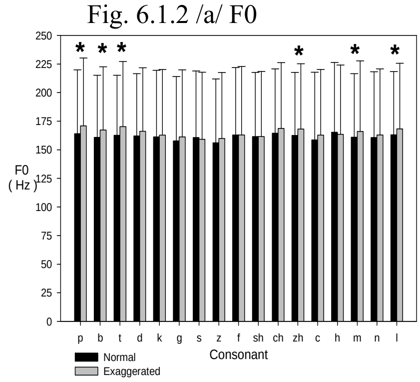


Fig. 6.1.3 /u/ F0

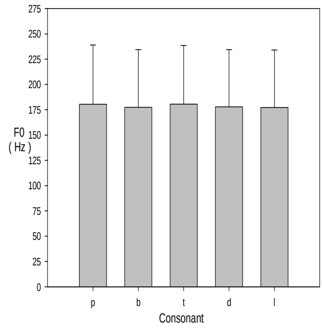


Fig. 6.2.1 /i/ %shimmer

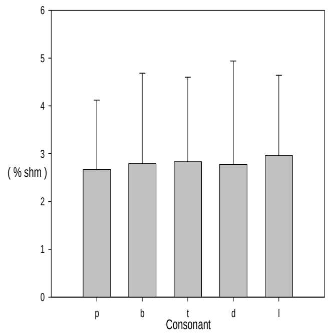


Fig. 6.2.2 /a/ %shimmer

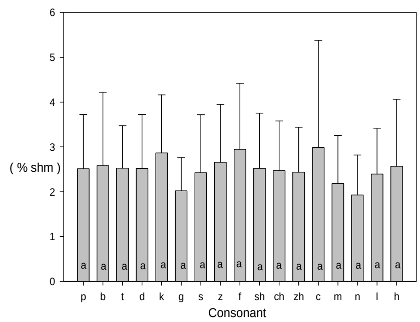


Fig. 6.2.3 /u/ %shimmer

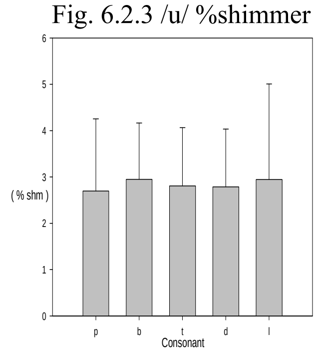


Fig. 6.3.1 /i/ SNR

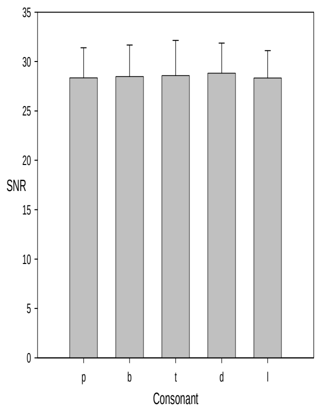


Fig. 6.3.2 /a/ SNR

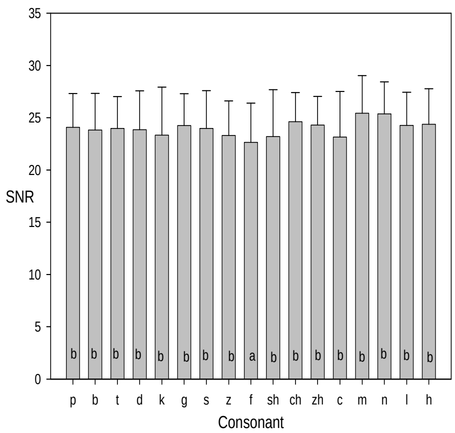


Fig. 6.3.3 /u/ SNR

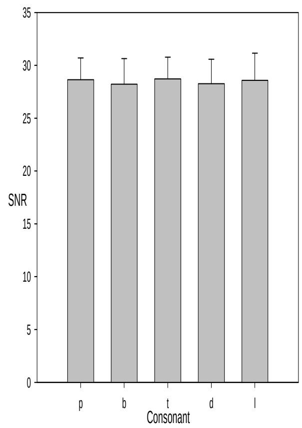


Figure 6. Consonant effect on F0, %shimmer, and SNR for the Mandarin group in vowels /i/, /a/, and /u/ separately. (Consonants with a significant difference on the measure were marked with different letters. Notation: p = /p'/, b = /p/, t = /t'/, d = /t/, z = /ts/, sh = /ʂ/, ch = /tʂ'/, zh = /tʂ/, c = /ts'/)

Fig. 7.1 /i/ F0

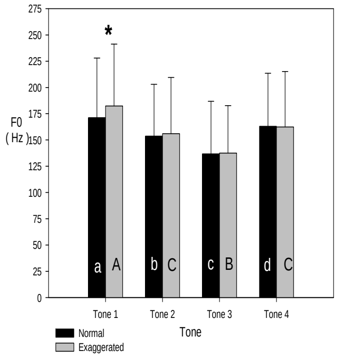


Fig. 7.2 /a/ F0

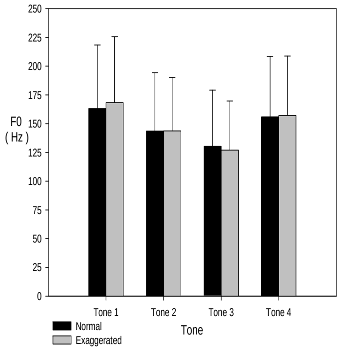


Fig. 7.3 /u/ F0

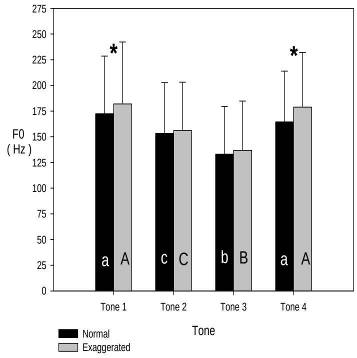


Figure 7. Tone effect on F0 for the Mandarin group in vowels /i/, /a/, and /u/ separately. (Significantly different between-task pairs were marked with “*”. Within-task consonants with significantly different F0 were marked with different letters, with those in the normal task using non-capitalized and those in the exaggerated jaw opening task using capitalized letters.)

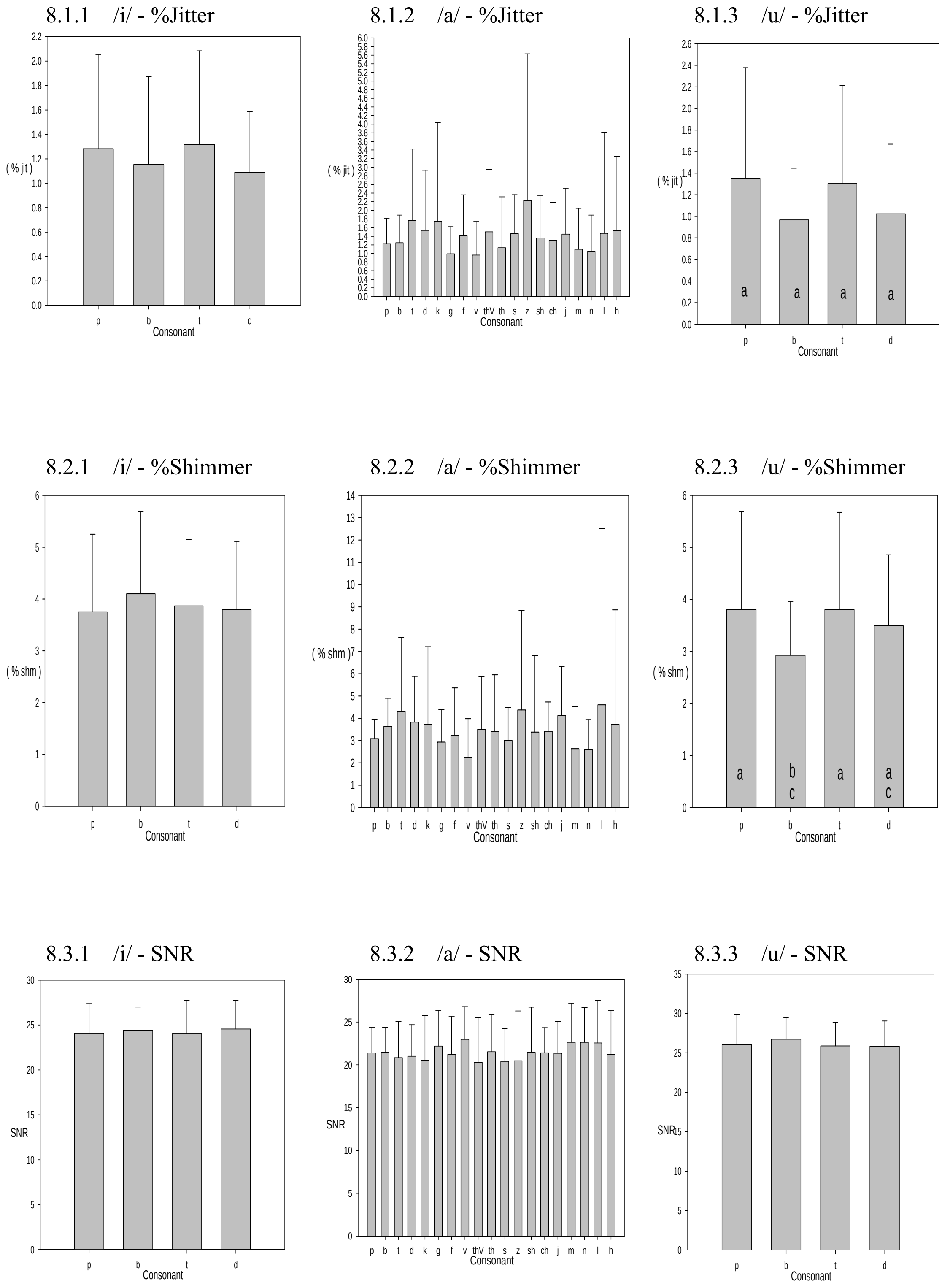


Figure 8. Consonant effect on %jitter, %shimmer, and SNR for the English group in the vowels /i/, /a/, and /u/ separately. (Consonants with a significant difference on the measure were marked with different letters. Notation: thV = /ð/, th = /θ/, sh = /ʃ/, ch = /tʃ/, j = /ʤ/)

Fig. 9.1.1 /i/ %jitter

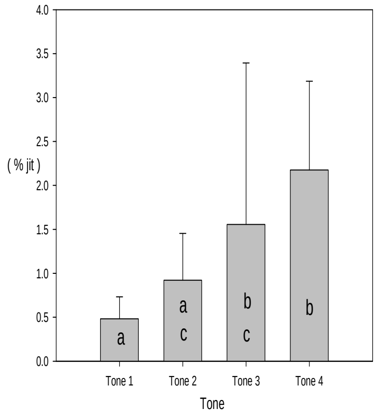


Fig. 9.1.2 /a/ %jitter

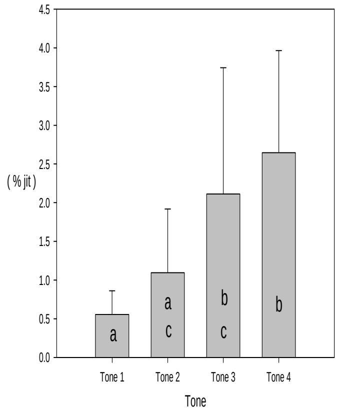


Fig. 9.1.3 /u/ %jitter

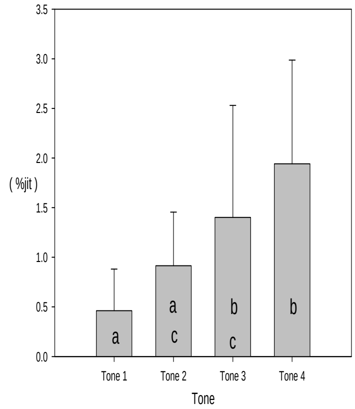


Fig. 9.2.1 /i/ %shimmer

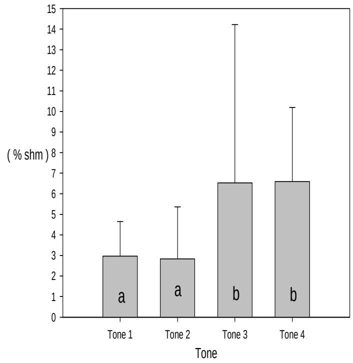


Fig. 9.2.2 /a/ %shimmer

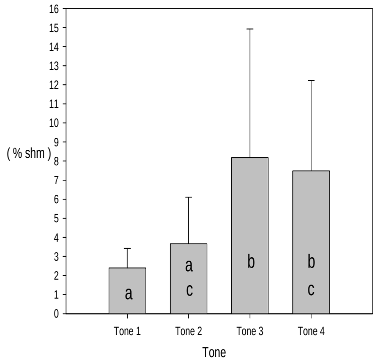


Fig. 9.2.3 /u/ %shimmer

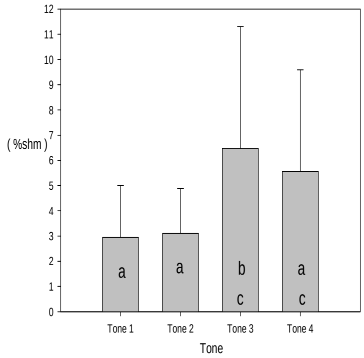


Fig. 9.3.1 /i/ SNR

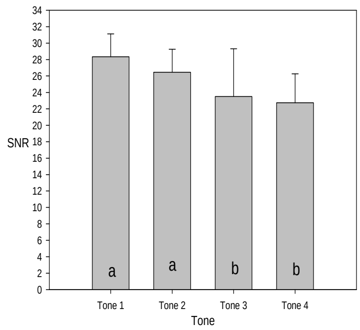


Fig. 9.3.2 /a/ SNR

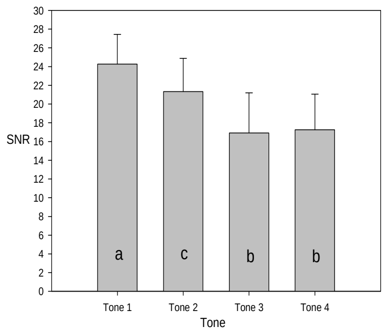


Fig. 9.3.3 /u/ SNR

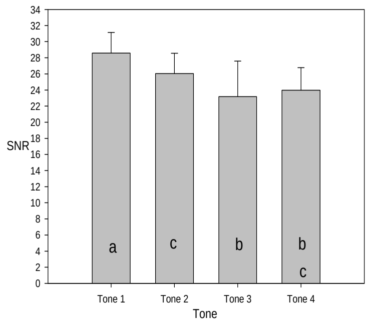


Figure 9. Tone effect on %jitter, %shimmer, and SNR for the Mandarin group in vowels /i, a, u/ separately. (Tones with a significant difference on the measure were marked with different letters.)

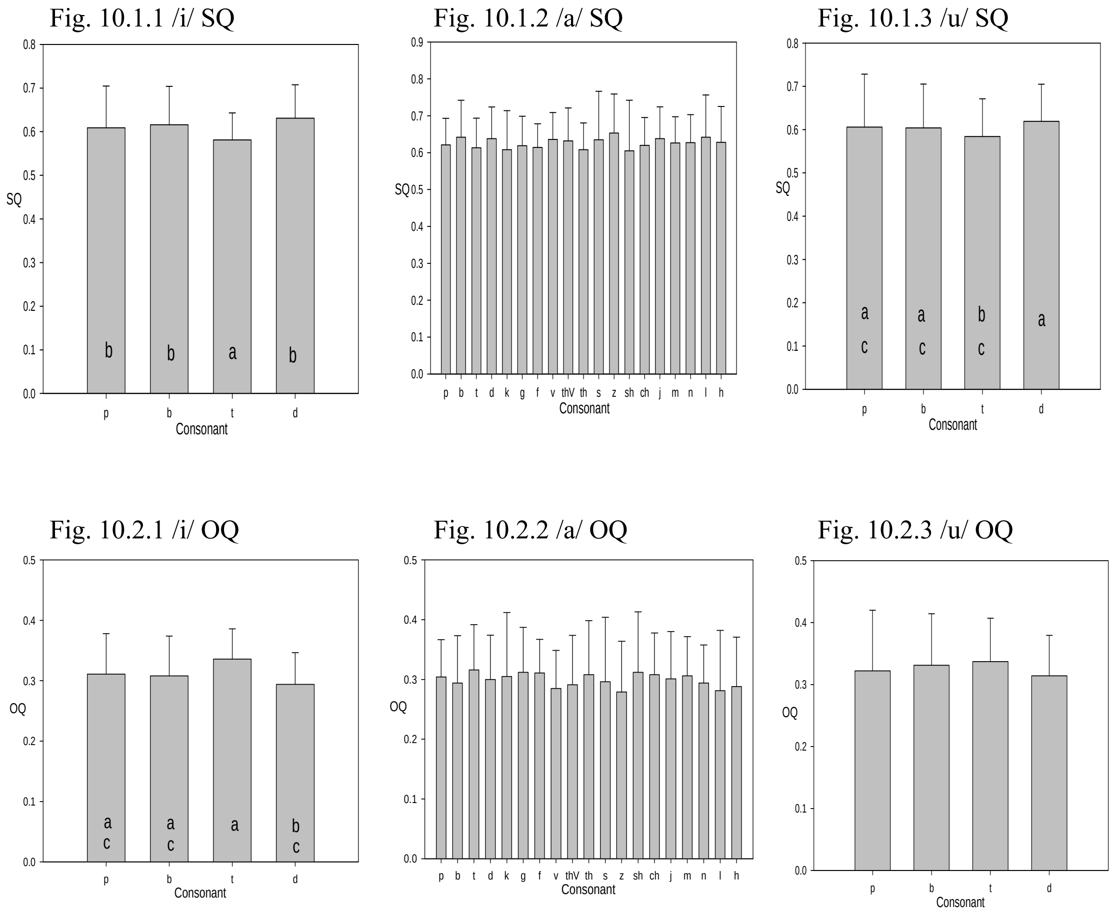


Figure 10. Consonant effect on Speed Quotient (SQ) and Open Quotient (OQ) for the English group in vowels /i, a, u/ separately. (Consonants with a significant difference on the measure were marked with different letters.) Notation: thV = /ð/, th = /θ/, sh = /ʃ/, ch = /tʃ/, j = /ʤ/).

Fig. 11.1 /a/ - SQ

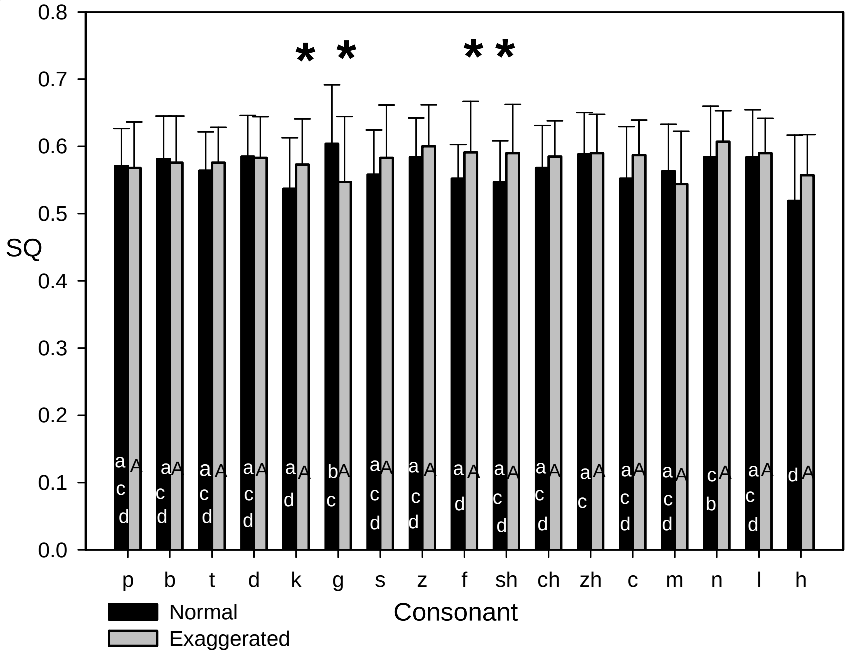


Fig. 11.2 /a/ - OQ

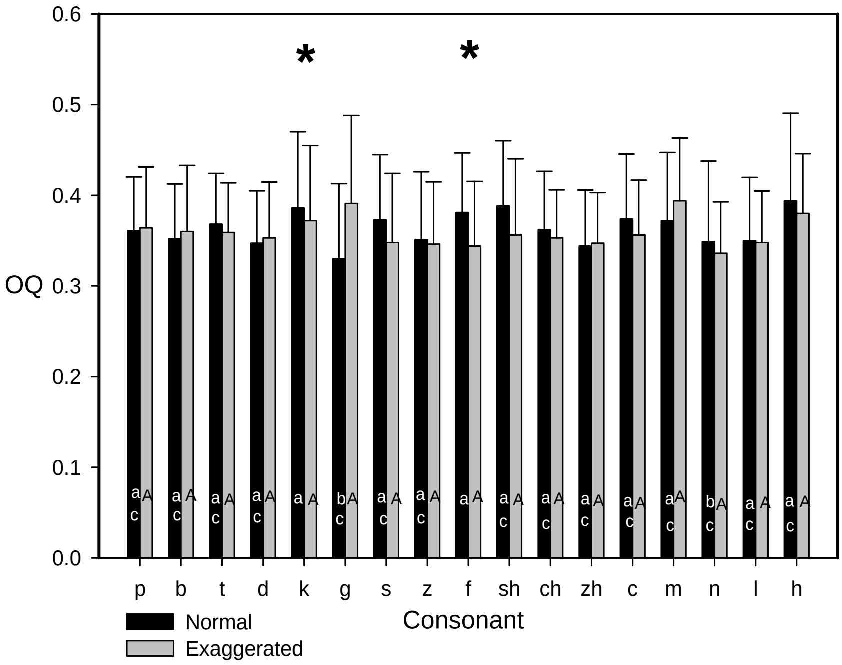


Figure 11. Means and standard deviations of Speed Quotient (SQ) and Open Quotient (OQ) for the normal and exaggerated jaw opening tasks across consonants in the Mandarin group for vowel /a/. (Significantly different between-task pairs were marked with “*”. Within-task consonants with significantly different F0 were marked with different letters, with those in the normal task using non-capitalized and those in the exaggerated jaw opening task using capitalized letters; Notation: p = /p’/, b = /p/, t = /t’/, d = /t/, z = /ts/, sh = /ʂ/, ch = /tʂ’/, zh = /tʂ/, c = /ts’/)

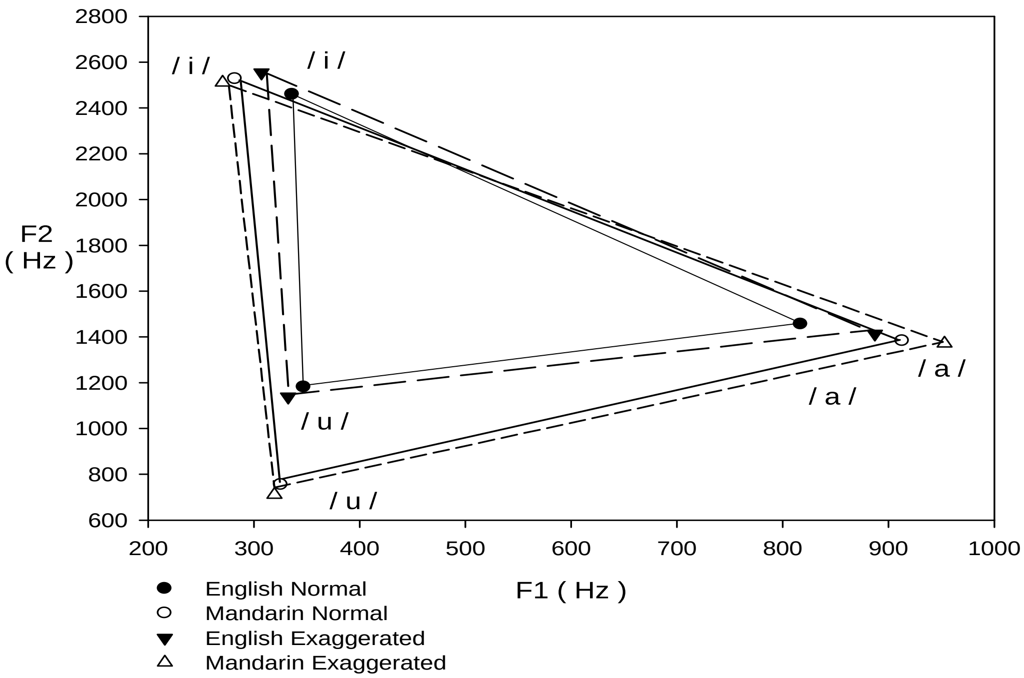


Figure 12. Vowel space for the normal and exaggerated jaw opening tasks in the English and Mandarin groups separately.

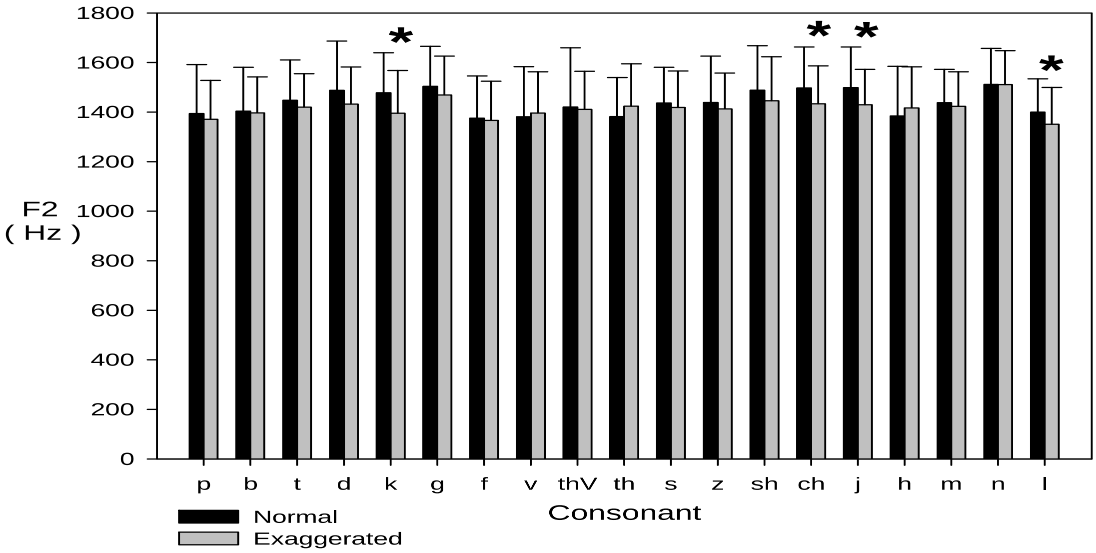


Figure 13. Means and standard deviations of F2 for the normal and exaggerated jaw opening tasks across consonants in the English group for vowel /a/. (Significantly different pairs were marked with "*". Notation: thV = /ð/, th = /θ/, sh = /ʃ/, ch = /tʃ/, j = /ʤ/).

Fig. 14.1 /a/ - F1

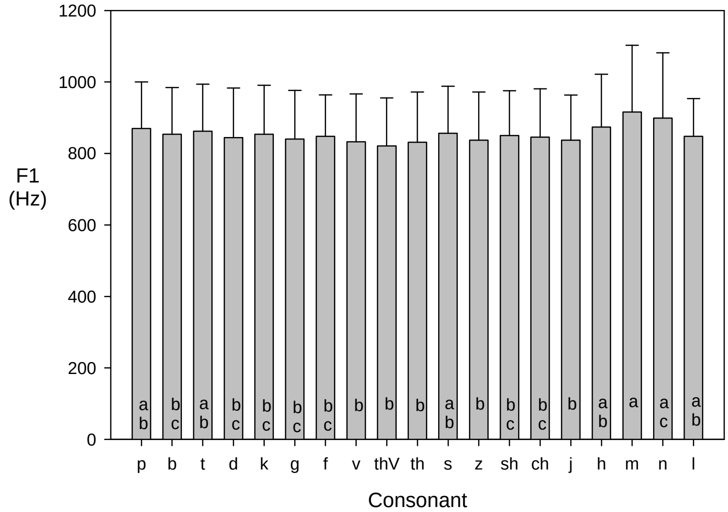


Fig. 14.2 /u/ - F1

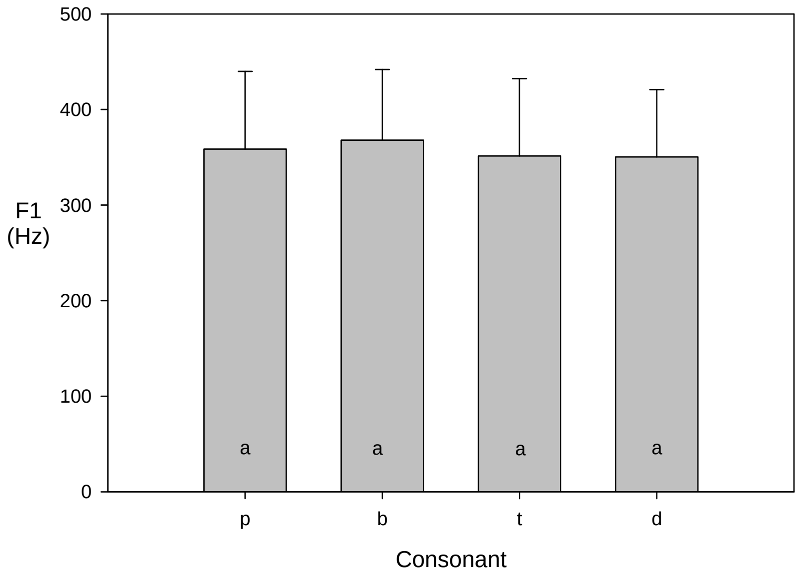


Figure 14. Means and standard deviations of F1 across consonants for the English group in vowels /a/ and /u/ respectively. (Consonants with significantly different F1 were marked with different letters. Notation: thV = /ð/, th = /θ/, sh = /ʃ/, ch = /tʃ/, j = /ʤ/).

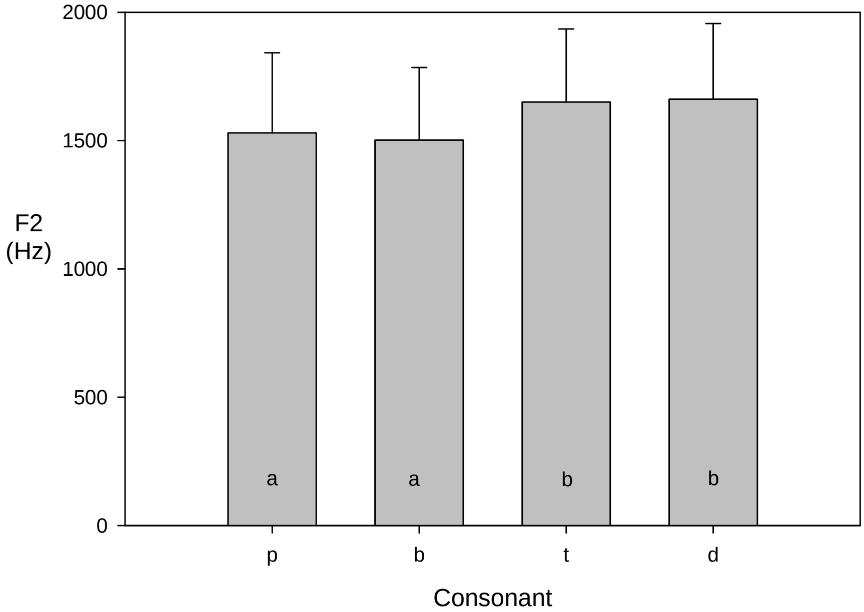


Figure 15. Means and standard deviations of F2 across consonants for the English group in vowel /u/. (Consonants with significantly different F2 were marked with different letters.)

Fig. 16.1 /u/ - F1

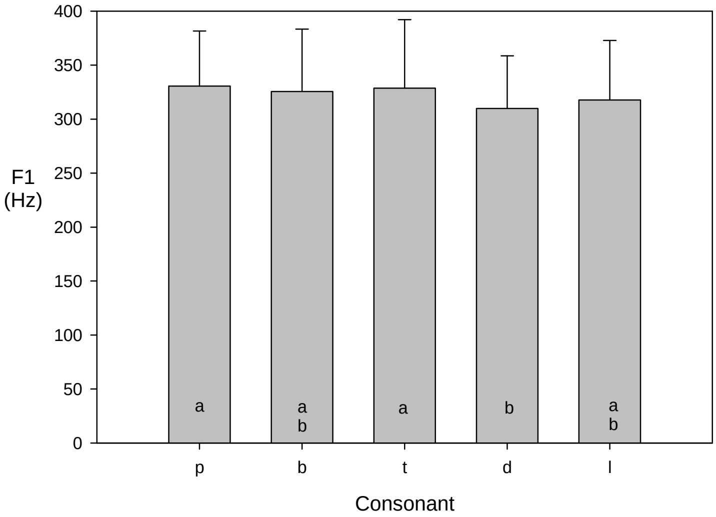


Fig. 16.1 /a/ - F2

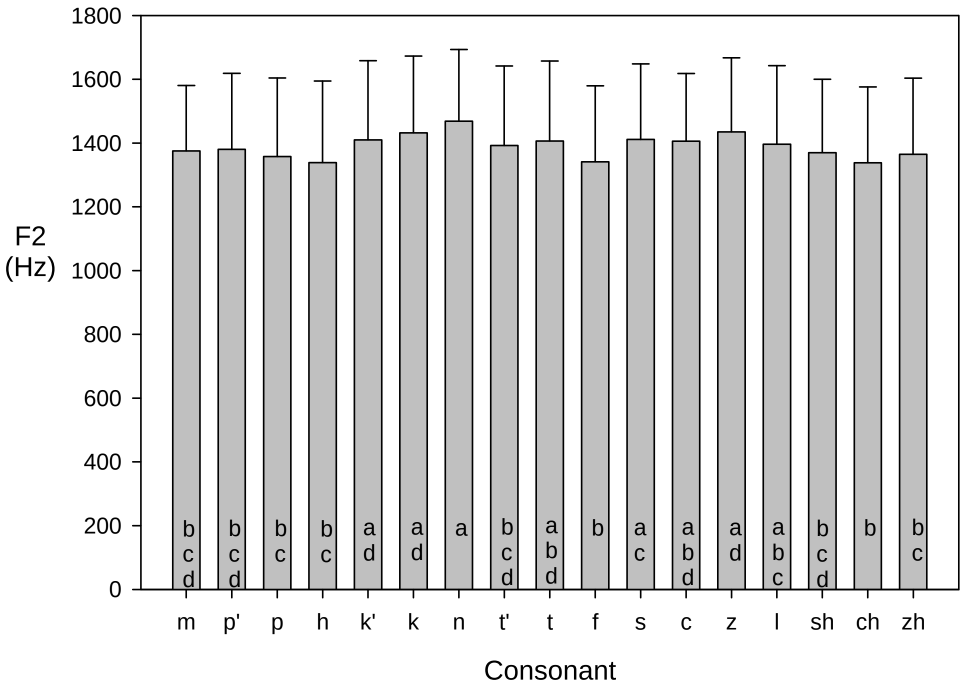
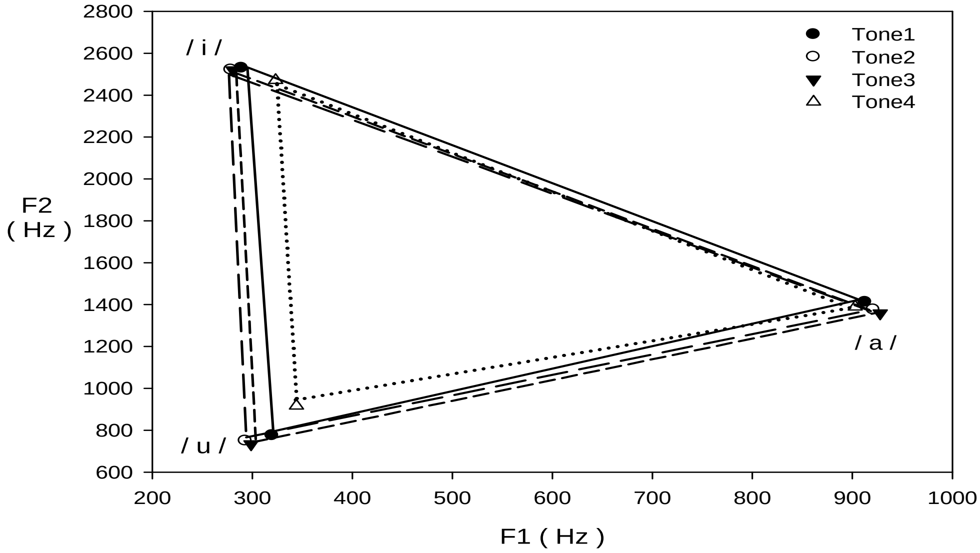


Figure 16. Means and standard deviations of F1 for vowels /u/ and of F2 for vowel /a/ across consonants in the Mandarin group. (Consonants with significantly different F2 were marked with different letters. Notation: p = /p'/, b = /p/, t = /t'/, d = /t/, z = /ts/, sh = /ʂ/, ch = /tʂ'/, zh = /tʂ/, c = /ts'/)

Normal



Exaggerated (Jaw Opening)

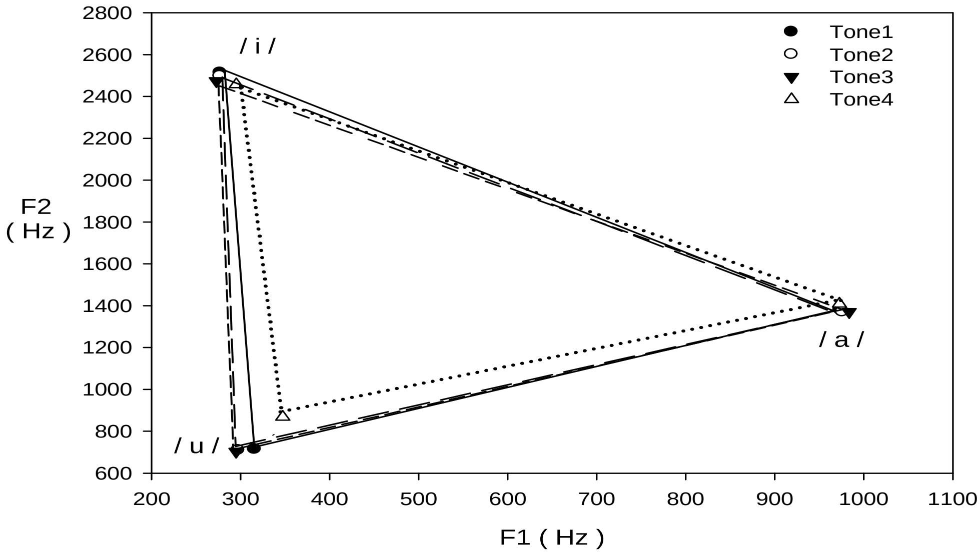


Figure 17. Tone effect on the vowel space in the normal and exaggerated jaw opening tasks separately.

Fig. 18.1.1 English - /i/

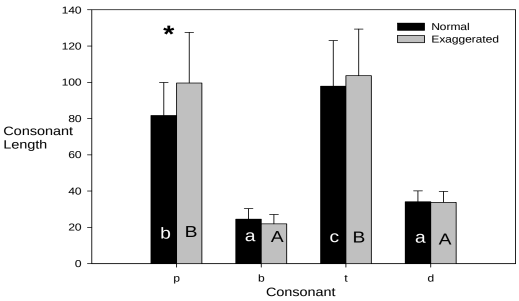


Fig. 18.1.2 Mandarin - /i/

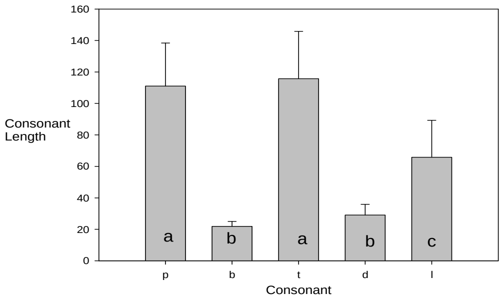


Fig. 18.2.1 English - /a/

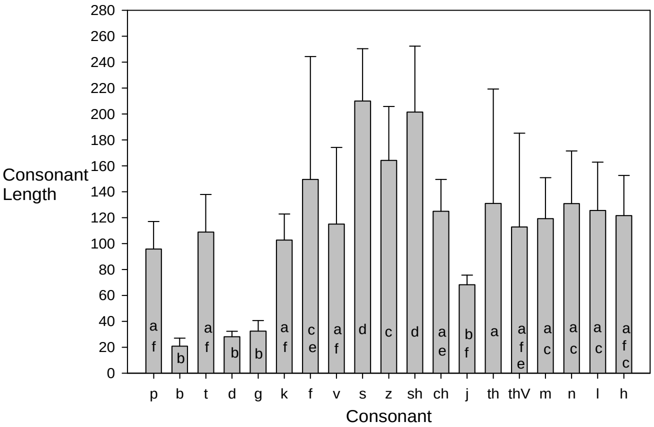


Fig. 18.2.2 Mandarin - /a/

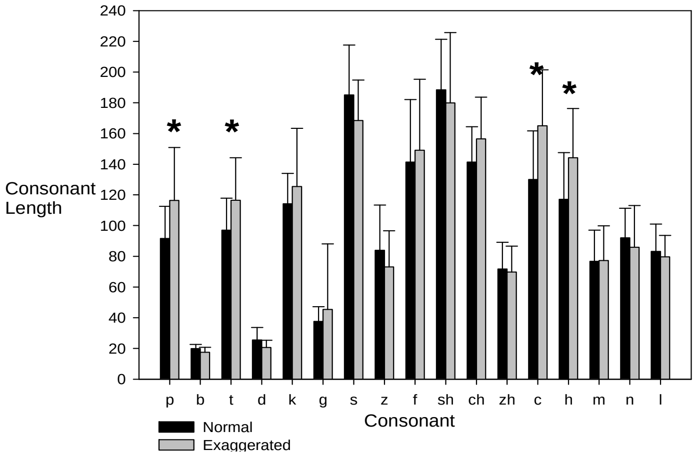


Fig. 18.3.1 English - /u/

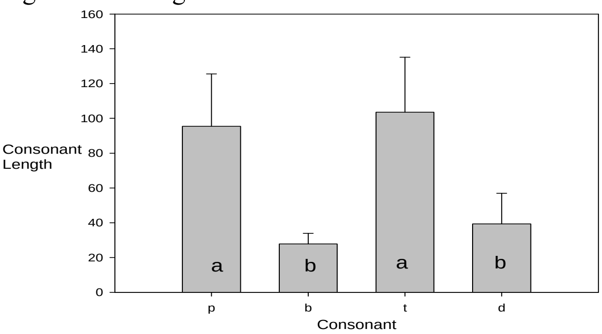


Fig. 18.3.2 Mandarin - /u/

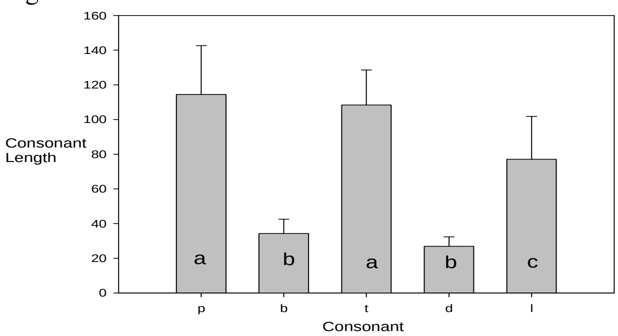


Figure 18. Consonant and consonant-by-task interaction effect on consonant length for English and Mandarin Groups in vowels /i, a, u/ separately. (Notation: For English, thV = /ð/, th = /θ/, sh = /ʃ/, ch = /tʃ/, j = /ʤ/; For Mandarin, p = /p'/, b = /p/, t = /t'/, d = /t/, z = /ts/, sh = /ʂ/, ch = /tʂ'/, zh = /tʂ/, c = /ts'/)

Appendix 1

General Information for Individual Participants

Subject Code	Gender	Age (in years)
English Group		
English M1*	Male	28
English M2	Male	51
English M3	Male	57
English M4	Male	43
English M5	Male	23
English F1	Female	20
English F2	Female	50
English F3	Female	45
English F4	Female	24
English F5	Female	24
Mandarin Group		
Mandarin M1	Male	30
Mandarin M2	Male	22
Mandarin M3	Male	24
Mandarin M4	Male	25
Mandarin M5	Male	19
Mandarin F1	Female	43
Mandarin F2	Female	19
Mandarin F3	Female	45
Mandarin F4	Female	24
Mandarin F4	Female	24

*The label “English” or “Mandarin” shows the speaker’s mother tongue and ‘M1-5’ or ‘F1-5’ stands for the gender and the randomly assigned subject numbering, with “M” denoting “male” and “F” female.)

Appendix 2

Two-way (Consonant by Task) ANOVA Results for Individual English Speakers – Jaw Opening

Subject	N	Consonant Effect	Task Effect	Consonant x Task Interaction Effect
/i/				
English M1	40	$F(3, 32) = 1.898$, $p = 0.150$	$F(1, 32) = 19.64$, $p < 0.001$**	$F(3, 32) = 1.371$, $p = 0.269$
English M2	40	$F(3, 32) = 4.920$, $p = 0.006$*	$F(1, 32) = 64.40$, $p < 0.001$**	$F(3, 32) = 3.039$, $p = 0.043$*
English M3	38†	$F(3, 30) = 0.030$, $p = 0.993$	$F(1, 30) = 146.1$, $p < 0.001$**	$F(3, 30) = 1.233$, $p = 0.315$
English M4	40	$F(3, 32) = 0.876$, $p = 0.464$	$F(1, 32) = 3.965$, $p = 0.055$	$F(3, 32) = 0.067$, $p = 0.977$
English M5	39†	$F(3, 31) = 6.457$, $p = 0.002$**	$F(1, 31) = 36.41$, $p < 0.001$**	$F(3, 31) = 3.906$, $p = 0.018$*
English F1	40	$F(3, 32) = 2.485$, $p = 0.078$	$F(1, 32) = 3.614$, $p = 0.066$	$F(3, 32) = 1.463$, $p = 0.243$
English F2	40	$F(3, 32) = 1.368$, $p = 0.270$	$F(1, 32) = 2.468$, $p = 0.126$	$F(3, 32) = 0.153$, $p = 0.927$
English F3	40	$F(3, 32) = 1.746$, $p = 0.177$	$F(1, 32) = 9.914$, $p = 0.004$**	$F(3, 32) = 1.235$, $p = 0.313$
English F4	40	$F(3, 32) = 0.484$, $p = 0.695$	$F(1, 32) = 6.201$, $p = 0.018$*	$F(3, 32) = 0.762$, $p = 0.524$
English F5	40	$F(3, 32) = 5.498$, $p = 0.004$**	$F(1, 32) = 13.72$, $p < 0.001$**	$F(3, 32) = 0.318$, $p = 0.812$
/a/				
English M1	60	$F(5, 48) = 0.777$, $p = 0.571$	$F(1, 48) = 326.23$, $p < 0.001$**	$F(5, 48) = 0.462$, $p = 0.803$
English M2	60	$F(5, 48) = 0.781$, $p = 0.569$	$F(1, 48) = 193.3$, $p < 0.001$**	$F(5, 48) = 0.692$, $p = 0.632$
English M3	55†	$F(5, 43) = 1.561$, $p = 0.191$	$F(1, 43) = 257.2$, $p < 0.001$**	$F(5, 43) = 2.491$, $p = 0.046$*
English M4	60	$F(5, 48) = 2.632$, $p = 0.035$*	$F(1, 48) = 219.2$, $p < 0.001$**	$F(1, 48) = 0.857$, $p = 0.517$
English M5	56†	$F(5, 44) = 0.684$, $p = 0.638$	$F(1, 44) = 77.97$, $p < 0.001$**	$F(5, 44) = 0.214$, $p = 0.955$
English F1	60	$F(5, 48) = 2.259$, $p = 0.063$	$F(1, 48) = 40.86$, $p < 0.001$**	$F(5, 48) = 2.415$, $p = 0.049$*
English F2	59†	$F(5, 47) = 1.673$, $p = 0.160$	$F(1, 47) = 36.89$, $p < 0.001$ **	$F(5, 47) = 1.646$, $p = 0.167$
English F3	60	$F(5, 48) = 1.850$, $p = 0.121$	$F(1, 48) = 57.41$, $p < 0.001$**	$F(5, 48) = 0.425$, $p = 0.829$
English F4	60	$F(5, 48) = 1.368$, $p = 0.253$	$F(1, 48) = 121.2$, $p < 0.001$**	$F(5, 48) = 0.511$, $p = 0.767$
English F5	60	$F(5, 48) = 2.035$, $p = 0.090$	$F(1, 48) = 62.80$, $p < 0.001$**	$F(5, 48) = 1.193$, $p = 0.327$
/u/				
English M1	39†	$F(3, 31) = 3.365$, $p = 0.031$*	$F(1, 31) = 25.76$, $p < 0.001$**	$F(3, 31) = 2.871$, $p = 0.052$
English M2	40	$F(3, 32) = 2.911$, $p = 0.049$*	$F(1, 32) = 113.6$, $p < 0.001$**	$F(3, 32) = 0.657$, $p = 0.585$
English M3	22†	$F(3, 17) = 1.010$, $p = 0.412$	$F(1, 17) = 21.69$, $p < 0.001$**	--
English M4	40	$F(3, 32) = 1.241$, $p = 0.311$	$F(1, 32) = 11.70$, $p = 0.002$**	$F(3, 32) = 0.102$, $p = 0.958$
English M5	39†	$F(3, 31) = 4.856$, $p = 0.007$*	$F(1, 31) = 12.56$, $p < 0.001$**	$F(3, 31) = 0.309$, $p = 0.819$
English F1	40	$F(3, 32) = 1.655$, $p = 0.196$	$F(1, 32) = 0.481$, $p = 0.493$	$F(3, 32) = 1.176$, $p = 0.334$
English F2	40	$F(3, 32) = 0.433$, $p = 0.731$	$F(1, 32) = 0.131$, $p = 0.720$	$F(3, 32) = 0.302$, $p = 0.824$
English F3	36†	$F(3, 28) = 1.033$, $p = 0.393$	$F(1, 28) = 18.63$, $p < 0.001$**	$F(3, 28) = 0.619$, $p = 0.609$
English F4	40	$F(3, 32) = 0.367$, $p = 0.777$	$F(1, 32) = 24.50$, $p < 0.001$**	$F(3, 32) = 0.400$, $p = 0.754$
English F5	40	$F(3, 32) = 6.545$, $p = 0.001$**	$F(1, 32) = 0.519$, $p = 0.476$	$F(3, 32) = 1.694$, $p = 0.188$

*Significant at 0.05 level
**Significant at 0.005 level
†Missing data

Appendix 3

Two-way (Consonant by Task) ANOVA Results for Individual Mandarin Speakers – Jaw Opening

Subject	N	Consonant Effect	Task Effect	Consonant x Task Interaction Effect
/i/				
Mandarin M1	47†	$F(4, 37) = 5.436$, $p = 0.002$**	$F(1, 37) = 5.839$, $p = 0.021$*	$F(4, 37) = 0.943$, $p = 0.450$
Mandarin M2	49†	$F(4, 39) = 0.555$, $p = 0.697$	$F(1, 39) = 4.986$, $p = 0.031$*	$F(4, 39) = 3.664$, $p = 0.013$*
Mandarin M3	50	$F(4, 40) = 1.177$, $p = 0.335$	$F(1, 40) = 34.51$, $p < 0.001$**	$F(4, 40) = 0.917$, $p = 0.463$
Mandarin M4	49†	$F(4, 39) = 1.339$, $p = 0.273$	$F(1, 39) = 9.462$, $p = 0.004$**	$F(4, 39) = 0.376$, $p = 0.825$
Mandarin M5	50	$F(4, 40) = 4.148$, $p = 0.007$*	$F(1, 40) = 150.9$, $p < 0.001$**	$F(4, 40) = 0.552$, $p = 0.699$
Mandarin F2	49†	$F(4, 39) = 0.743$, $p = 0.569$	$F(1, 39) = 36.97$, $p < 0.001$**	$F(4, 39) = 1.414$, $p = 0.248$
Mandarin F3	50	$F(4, 40) = 6.111$, $p < 0.001$**	$F(1, 40) = 6.504$, $p = 0.015$*	$F(4, 40) = 1.837$, $p = 0.141$
Mandarin F4	48†	$F(4, 38) = 1.658$, $p = 0.180$	$F(1, 38) = 32.11$, $p < 0.001$**	$F(4, 38) = 0.555$, $p = 0.697$
Mandarin F5	50	$F(4, 40) = 2.138$, $p = 0.094$	$F(1, 40) = 64.23$, $p < 0.001$**	$F(4, 40) = 3.639$, $p = 0.013$*
/a/				
Mandarin M1	63†	$F(6, 49) = 0.446$, $p = 0.845$	$F(1, 49) = 54.50$, $p < 0.001$**	$F(4, 49) = 0.410$, $p = 0.869$
Mandarin M2	70	$F(6, 56) = 3.918$, $p = 0.002$**	$F(1, 56) = 300.6$, $p < 0.001$**	$F(6, 56) = 1.018$, $p = 0.423$
Mandarin M3	70	$F(6, 56) = 2.089$, $p = 0.069$	$F(1, 56) = 124.43$, $p < 0.001$**	$F(6, 56) = 0.949$, $p = 0.468$
Mandarin M4	65†	$F(6, 51) = 1.261$, $p = 0.291$	$F(1, 51) = 40.723$, $p < 0.001$**	$F(6, 51) = 0.956$, $p = 0.464$
Mandarin M5	70	$F(6, 56) = 0.856$, $p = 0.533$	$F(1, 56) = 442.06$, $p < 0.001$**	$F(6, 56) = 1.204$, $p = 0.318$
Mandarin F2	60†	$F(6, 46) = 2.212$, $p = 0.059$	$F(1, 46) = 139.07$, $p < 0.001$**	$F(6, 46) = 0.451$, $p = 0.841$
Mandarin F3	70	$F(6, 56) = 0.613$, $p = 0.719$	$F(1, 56) = 148.70$, $p < 0.001$**	$F(6, 56) = 0.420$, $p = 0.863$
Mandarin F4	67†	$F(6, 53) = 4.415$, $p = 0.001$**	$F(1, 53) = 132.25$, $p < 0.001$**	$F(6, 53) = 0.918$, $p = 0.490$
Mandarin F5	70	$F(6, 56) = 2.715$, $p = 0.022$*	$F(1, 56) = 181.30$, $p < 0.001$**	$F(6, 56) = 0.630$, $p = 0.706$
/u/				
Mandarin M1	17†	$F(4, 11) = 1.144$, $p = 0.386$	$F(1, 11) = 0.0215$, $p = 0.886$	--
Mandarin M2	50	$F(4, 40) = 0.524$, $p = 0.719$	$F(1, 40) = 34.712$, $p < 0.001$**	$F(4, 40) = 1.385$, $p = 0.256$
Mandarin M3	50	$F(4, 40) = 2.345$, $p = 0.071$	$F(1, 40) = 0.0352$, $p = 0.852$	$F(4, 40) = 2.877$, $p = 0.035$*
Mandarin M4	20†	$F(4, 14) = 2.722$, $p = 0.072$	$F(1, 14) = 5.9790$, $p = 0.028$*	--
Mandarin M5	49†	$F(4, 39) = 1.109$, $p = 0.366$	$F(1,39) = 91.149$, $p < 0.001$**	$F(4, 39) = 0.749$, $p = 0.565$
Mandarin F2	42†	$F(4, 32) = 0.551$, $p = 0.700$	$F(1,32) = 60.580$, $p < 0.001$**	$F(4, 40) = 3.696$, $p = 0.014$*
Mandarin F3	48†	$F(4, 38) = 0.721$, $p = 0.583$	$F(1, 38) = 53.65$, $p < 0.001$**	$F(4, 38) = 0.711$, $p = 0.589$
Mandarin F4	46†	$F(4, 36) = 1.324$, $p = 0.280$	$F(1, 36) = 20.35$, $p < 0.001$**	$F(4, 36) = 1.248$, $p = 0.308$
Mandarin F5	48†	$F(4, 38) = 8.058$, $p < 0.001$**	$F(1, 38) = 22.57$, $p < 0.001$**	$F(4, 38) = 0.963$, $p = 0.439$

*Significant at 0.05 level
**Significant at 0.005 level
†Missing data

Appendix 4

Two-way (Tone by Task) ANOVA Results for Individual Mandarin Speakers – Jaw Opening

Subject	N	Tone Effect	Task Effect	Tone x Task Interaction Effect
/i/				
Mandarin M1	39†	$F(3, 31) = 1.311, p = 0.288$	$F(1, 31) = 1.170, p = 0.288$	$F(3, 31) = 0.338, p = 0.798$
Mandarin M2	38†	$F(3, 30) = 0.817, p = 0.494$	$F(1, 30) = 0.0004, p = 0.985$	$F(3, 30) = 0.992, p = 0.410$
Mandarin M3	40	$F(3, 32) = 2.400, p = 0.086$	$F(1, 32) = 18.51, p < 0.001$**	$F(3, 32) = 0.613, p = 0.611$
Mandarin M4	38†	$F(3, 30) = 0.833, p = 0.486$	$F(1, 30) = 1.582, p = 0.218$	$F(3, 30) = 0.796, p = 0.506$
Mandarin M5	40	$F(3, 32) = 0.936, p = 0.435$	$F(1, 32) = 159.0, p < 0.001$**	$F(3, 32) = 0.113, p = 0.952$
Mandarin F2	36†	$F(3, 28) = 1.044, p = 0.389$	$F(1, 28) = 44.63, p < 0.001$**	$F(3, 28) = 1.153, p = 0.345$
Mandarin F3	40	$F(3, 32) = 0.840, p = 0.482$	$F(1, 32) = 13.58, p < 0.001$**	$F(3, 32) = 0.592, p = 0.625$
Mandarin F4	38†	$F(3, 30) = 0.825, p = 0.490$	$F(1, 30) = 45.98, p < 0.001$**	$F(3, 30) = 1.171, p = 0.337$
Mandarin F5	40	$F(3, 32) = 1.009, p = 0.402$	$F(1, 32) = 33.00, p < 0.001$**	$F(3, 32) = 1.705, p = 0.186$
/a/				
Mandarin M1	37†	$F(3, 29) = 1.315, p = 0.289$	$F(1, 29) = 35.86, p < 0.001$**	$F(3, 29) = 1.485, p = 0.239$
Mandarin M2	40	$F(3, 32) = 3.591, p = 0.024$*	$F(1, 32) = 192.5, p < 0.001$**	$F(3, 32) = 2.247, p = 0.102$
Mandarin M3	40	$F(3, 32) = 0.517, p = 0.674$	$F(1, 32) = 69.56, p < 0.001$**	$F(3, 32) = 0.907, p = 0.449$
Mandarin M4	37†	$F(3, 29) = 0.292, p = 0.831$	$F(1, 29) = 4.004, p = 0.055$	$F(3, 29) = 0.684, p = 0.569$
Mandarin M5	40	$F(3, 32) = 1.030, p = 0.392$	$F(1, 32) = 223.5, p < 0.001$**	$F(3, 32) = 1.534, p = 0.225$
Mandarin F2	34†	$F(3, 26) = 2.262, p = 0.105$	$F(1, 26) = 94.33, p < 0.001$**	$F(3, 26) = 2.964, p = 0.051$
Mandarin F3	40	$F(3, 32) = 1.582, p = 0.213$	$F(1, 32) = 113.6, p < 0.001$**	$F(3, 32) = 0.849, p = 0.478$
Mandarin F4	39†	$F(3, 31) = 2.702, p = 0.063$	$F(1, 31) = 56.95, p < 0.001$**	$F(3, 31) = 1.010, p = 0.402$
Mandarin F5	40	$F(3, 32) = 2.237, p = 0.103$	$F(1, 32) = 125.2, p < 0.001$**	$F(3, 32) = 1.452, p = 0.246$
/u/				
Mandarin M1	17†	--	--	--
Mandarin M2	40	$F(3, 32) = 1.112, p = 0.359$	$F(1, 32) = 15.03, p < 0.001$**	$F(3, 32) = 1.005, p = 0.403$
Mandarin M3	40	$F(3, 32) = 0.354, p = 0.787$	$F(1, 32) = 0.013, p = 0.911$	$F(3, 32) = 1.402, p = 0.260$
Mandarin M4	7†	--	--	--
Mandarin M5	40	$F(3, 32) = 1.610, p = 0.206$	$F(1, 32) = 142.5, p < 0.001$**	$F(4, 32) = 0.655, p = 0.586$
Mandarin F2	36†	$F(3, 28) = 0.570, p = 0.639$	$F(1, 28) = 40.70, p < 0.001$**	$F(3, 28) = 0.946, p = 0.432$
Mandarin F3	40	$F(3, 32) = 0.085, p = 0.968$	$F(1, 32) = 28.35, p < 0.001$**	$F(3, 32) = 0.235, p = 0.871$
Mandarin F4	38†	$F(3, 30) = 0.885, p = 0.460$	$F(1, 30) = 31.47, p < 0.001$**	$F(4, 30) = 0.239, p = 0.869$
Mandarin F5	38†	$F(3, 30) = 1.069, p = 0.377$	$F(1, 30) = 32.87, p < 0.001$**	$F(3, 30) = 1.525, p = 0.228$

*Significant at 0.05 level
**Significant at 0.005 level
†Missing data

Appendix 5

Two-way (Consonant by Task) ANOVA Results for Individual English Speakers – F1

Subject	N	Consonant Effect	Task Effect	Consonant x Task Interaction Effect
/i/				
English M1	40	$F(3, 32) = 1.391, p = 0.285$	$F(1, 32) = 9.950, p = 0.003$**	$F(3, 32) = 7.387, p < 0.001$**
English M2	40	$F(3, 32) = 0.227, p = 0.877$	$F(1, 32) = 8.025, p = 0.008$**	$F(3, 32) = 5.361, p = 0.004$**
English M3	40	$F(3, 32) = 1.520, p = 0.228$	$F(1, 32) = 28.33, p < 0.001$**	$F(3, 32) = 0.819, p = 0.493$
English M4	40	$F(3, 32) = 0.783, p = 0.512$	$F(1, 32) = 2.426, p = 0.129$	$F(3, 32) = 0.789, p = 0.506$
English M5	40	$F(3, 32) = 2.308, p = 0.095$	$F(1, 32) = 0.013, p = 0.909$	$F(3, 32) = 0.517, p = 0.674$
English F1	40	$F(3, 32) = 0.772, p = 0.518$	$F(1, 32) = 10.54, p = 0.003$**	$F(3, 32) = 0.789, p = 0.509$
EnglishF2	40	$F(3, 32) = 0.413, p = 0.745$	$F(1, 32) = 0.450, p = 0.507$	$F(3, 32) = 0.651, p = 0.588$
English F3	40	$F(3, 32) = 0.088, p = 0.966$	$F(1, 32) = 19.04, p < 0.001$**	$F(3, 32) = 0.320, p = 0.811$
English F4	40	$F(3, 32) = 0.811, p = 0.497$	$F(1, 32) = 122.2, p < 0.001$**	$F(3, 32) = 4.026, p = 0.015$*
English F5	40	$F(3, 32) = 2.097, p = 0.120$	$F(1, 32) = 1.806, p = 0.188$	$F(3, 32) = 0.222, p = 0.880$
/a/				
English M1	60	$F(5, 48) = 0.487, p = 0.786$	$F(1, 48) = 56.51, p < 0.001$**	$F(5, 48) = 0.833, p = 0.533$
English M2	59†	$F(5, 47) = 2.194, p = 0.071$	$F(1, 47) = 31.59, p < 0.001$**	$F(5, 47) = 2.508, p = 0.043$*
English M3	60	$F(5, 48) = 1.649, p = 0.165$	$F(1, 48) = 13.35, p < 0.001$**	$F(5, 48) = 1.008, p = 0.423$
English M4	60	$F(5, 48) = 1.920, p = 0.108$	$F(1, 48) = 6.651, p = 0.013$*	$F(5, 48) = 0.759, p = 0.584$
English M5	60	$F(5, 48) = 1.232, p = 0.309$	$F(1, 48) = 134.4, p < 0.001$**	$F(5, 48) = 1.182, p = 0.332$
English F1	60	$F(5, 48) = 1.974, p = 0.099$	$F(1, 48) = 87.64, p < 0.001$**	$F(5, 48) = 0.840, p = 0.528$
English F2	60	$F(5, 48) = 2.426, p = 0.049$*	$F(1, 48) = 45.28, p < 0.001$**	$F(5, 48) = 3.045, p = 0.018$*
English F3	59†	$F(5, 47) = 0.880, p = 0.502$	$F(1, 47) = 51.30, p < 0.001$**	$F(5, 47) = 0.356, p = 0.875$
English F4	60	$F(5, 48) = 1.534, p = 0.197$	$F(1, 48) = 67.88, p < 0.001$**	$F(5, 48) = 1.453, p = 0.223$
English F5	60	$F(5, 48) = 1.294, p = 0.282$	$F(1, 48) = 0.274, p = 0.603$	$F(5, 48) = 0.514, p = 0.764$
/u/				
English M1	40	$F(3, 32) = 2.939, p = 0.048$*	$F(1, 32) = 26.48, p < 0.001$**	$F(3, 32) = 2.046, p = 0.127$
English M2	40	$F(3, 32) = 0.561, p = 0.645$	$F(1, 32) = 2.688, p = 0.111$	$F(3, 32) = 0.834, p = 0.485$
English M3	39†	$F(3, 31) = 2.289, p = 0.098$	$F(1, 31) = 12.08, p = 0.002$**	$F(3, 31) = 2.050, p = 0.127$
English M4	40	$F(3, 32) = 2.906, p = 0.050$*	$F(1, 32) = 9.377, p= 0.004$**	$F(3, 32) = 0.472, p = 0.704$
English M5	38†	$F(3, 30) = 2.524, p = 0.076$	$F(1, 30) = 9.819, p = 0.004$**	$F(3, 30) = 0.984, p = 0.414$
English F1	40	$F(3, 32) = 2.240, p= 0.103$	$F(1, 32) = 7.320, p = 0.011$*	$F(3, 32) = 2.179, p = 0.110$
English F2	40	$F(3, 32) = 0.051, p = 0.985$	$F(1, 32) = 4.296, p = 0.046$*	$F(3, 32) = 0.868, p = 0.468$
English F3	40	$F(3, 32) = 1.964, p = 0.139$	$F(1, 32) = 80.19, p < 0.001$**	$F(3, 32) = 0.369, p = 0.776$
English F4	40	$F(3, 32) = 0.709, p = 0.554$	$F(1, 32) = 0.373, p = 0.546$	$F(3, 32) = 1.963, p = 0.139$
English F5	38†	$F(3, 30) = 1.242, p = 0.312$	$F(1, 30) = 1.956, p = 0.172$	$F(3, 30) = 0.369, p = 0.776$

*Significant at 0.05 level
**Significant at 0.005 level
†Missing data

Appendix 6

Two-way (Consonant by Task) ANOVA Results for Individual Mandarin Speakers – F1

Subject	N	Consonant Effect	Task Effect	Consonant x Task Interaction Effect
/i/				
Mandarin M1	50	$F(4, 40) = 0.372, p = 0.827$	$F(1, 40) = 0.709, p = 0.405$	$F(4, 40) = 0.137, p = 0.968$
Mandarin M2	49†	$F(4, 39) = 0.868, p = 0.492$	$F(1, 39) = 2.416, p = 0.128$	$F(4, 39) = 0.827, p = 0.516$
Mandarin M3	50	$F(4, 40) = 1.276, p = 0.296$	$F(1, 40) = 1.536, p = 0.222$	$F(4, 40) = 0.633, p = 0.642$
Mandarin M4	50	$F(4, 40) = 1.498, p = 0.221$	$F(1, 40) = 13.41, p < 0.001$**	$F(4, 40) = 1.003, p = 0.417$
Mandarin M5	50	$F(4, 40) = 0.915, p = 0.465$	$F(1, 40) = 1.940, p = 0.171$	$F(4, 40) = 1.399, p = 0.252$
Mandarin F1	50	$F(4, 40) = 3.161, p = 0.024$*	$F(1, 40) = 16.58, p < 0.001$**	$F(4, 40) = 0.678, p = 0.611$
Mandarin F2	49†	$F(4, 39) = 0.528, p = 0.716$	$F(1, 39) = 1.672, p = 0.204$	$F(4, 39) = 2.340, p = 0.072$
Mandarin F3	49†	$F(4, 39) = 1.283, p = 0.293$	$F(1, 39) = 39.90, p < 0.001$**	$F(4, 39) = 1.703, p = 0.169$
Mandarin F4	50	$F(4, 40) = 1.758, p = 0.156$	$F(1, 40) = 14.21, p < 0.001$**	$F(4, 40) = 0.601, p = 0.664$
Mandarin F5	50	$F(4, 40) = 9.759, p < 0.001$**	$F(1, 40) = 39.09, p < 0.001$**	$F(4, 40) = 1.612, p = 0.196$
/a/				
Mandarin M1	70	$F(6, 56) = 5.412, p < 0.001$**	$F(1, 56) = 49.28, p < 0.001$**	$F(6, 56) = 0.612, p = 0.719$
Mandarin M2	68†	$F(6, 54) = 7.110, p < 0.001$**	$F(1, 54) = 25.07, p < 0.001$**	$F(6, 54) = 0.505, p = 0.802$
Mandarin M3	69†	$F(6, 55) = 1.396, p = 0.233$	$F(1, 55) = 0.200, p = 0.657$	$F(6, 55) = 0.974, p = 0.451$
Mandarin M4	69†	$F(6, 55) = 0.711, p = 0.642$	$F(1, 55) = 2.123, p = 0.151$	$F(6, 55) = 0.523, p = 0.789$
Mandarin M5	70	$F(6, 56) = 1.582, p = 0.170$	$F(1, 56) = 50.23, p < 0.001$**	$F(6, 56) = 0.682, p = 0.665$
Mandarin F1	69†	$F(6, 55) = 2.899, p = 0.016$*	$F(1, 55) = 40.81, p < 0.001$**	$F(6, 55) = 1.631, p = 0.156$
Mandarin F2	70	$F(6, 56) = 0.889, p = 0.510$	$F(1, 56) = 0.108, p = 0.743$	$F(6, 56) = 1.516, p = 0.190$
Mandarin F3	70	$F(6, 56) = 0.748, p = 0.614$	$F(1, 56) = 0.643, p = 0.426$	$F(6, 56) = 1.688, p = 0.141$
Mandarin F4	70	$F(6, 56) = 1.994, p = 0.082$	$F(1, 56) = 5.956, p = 0.018$*	$F(6, 56) = 1.554, p = 0.178$
Mandarin F5	70	$F(6, 56) = 0.403, p = 0.874$	$F(1, 56) = 18.03, p < 0.001$**	$F(6, 56) = 0.625, p = 0.709$
/u/				
Mandarin M1	50	$F(4, 40) = 5.302, p = 0.002$**	$F(1, 40) = 25.43, p < 0.001$**	$F(4, 40) = 1.315, p = 0.281$
Mandarin M2	50	$F(4, 40) = 1.226, p = 0.315$	$F(1, 40) = 19.31, p < 0.001$**	$F(4, 40) = 0.860, p = 0.496$
Mandarin M3	50	$F(4, 40) = 6.634, p < 0.001$**	$F(1, 40) = 55.77, p < 0.001$**	$F(4, 40) = 2.418, p = 0.064$
Mandarin M4	50	$F(4, 40) = 2.194, p = 0.087$	$F(1, 40) = 6.136, p = 0.018$*	$F(4, 40) = 0.305, p = 0.873$
Mandarin M5	50	$F(4, 40) = 1.571, p = 0.201$	$F(1, 40) = 13.58, p < 0.001$**	$F(4, 40) = 0.453, p = 0.770$
Mandarin F1	50	$F(4, 40) = 1.945, p = 0.122$	$F(1, 40) = 9.351, p = 0.004$**	$F(4, 40) = 1.525, p = 0.213$
Mandarin F2	50	$F(4, 40) = 2.384, p = 0.067$	$F(1, 40) = 10.33, p = 0.003$**	$F(4, 40) = 1.015, p = 0.411$
Mandarin F3	50	$F(4, 40) = 4.354, p = 0.005$**	$F(1, 40) = 0.00003, p = 0.995$	$F(4, 40) = 1.631, p = 0.185$
Mandarin F4	50	$F(4, 40) = 3.850, p = 0.010$*	$F(1, 40) = 24.334, p < 0.001$**	$F(4, 40) = 0.517, p = 0.724$
Mandarin F5	50	$F(4, 40) = 1.411, p = 0.248$	$F(1, 40) = 19.849, p < 0.001$**	$F(4, 40) = 1.637, p = 0.184$

*Significant at 0.05 level
**Significant at 0.005 level
†Missing data

Appendix 7

Two-way (Tone by Task) ANOVA Results for Individual Mandarin Speakers – F1

Subject	N	Tone Effect	Task Effect	Tone x Task Interaction Effect
/i/				
Mandarin M1	40	F(3, 32) = 6.769, p = 0.001**	F(1, 32) = 2.674, p = 0.112	F(3, 32) = 2.500, p = 0.077
Mandarin M2	40	F(3, 32) = 7.013, p < 0.001**	F(1, 32) = 10.23, p = 0.003**	F(3, 32) = 1.096, p = 0.365
Mandarin M3	40	F(3, 32) = 34.51, p < 0.001**	F(1, 32) = 2.135, p = 0.154	F(3, 32) = 5.285, p = 0.004**
Mandarin M4	40	F(3, 32) = 8.043, p < 0.001**	F(1, 32) = 0.044, p = 0.836	F(3, 32) = 2.471, p = 0.080
Mandarin M5	40	F(3, 32) = 0.903, p = 0.451	F(1, 32) = 1.698, p = 0.202	F(3, 32) = 1.224, p = 0.317
Mandarin F1	40	F(3, 32) = 5.933, p = 0.002**	F(1, 32) = 7.539, p = 0.010*	F(3, 32) = 3.735, p = 0.021*
Mandarin F2	40	F(3, 32) = 2.895, p = 0.050	F(1, 32) = 1.477, p = 0.233	F(3, 32) = 2.433, p = 0.083
Mandarin F3	40	F(3, 32) = 2.584, p = 0.070	F(1, 32) = 16.44, p < 0.001**	F(3, 32) = 5.172, p = 0.005**
Mandarin F4	40	F(3, 32) = 2.751, p = 0.059	F(1, 32) = 0.069, p = 0.795	F(3, 32) = 6.736, p = 0.001**
Mandarin F5	40	F(3, 32) = 0.977, p = 0.416	F(1, 32) = 8.110, p = 0.008**	F(3, 32) = 2.657, p = 0.065
/a/				
Mandarin M1	40	F(3, 32) = 0.279, p = 0.840	F(1, 32) = 10.62, p = 0.003**	F(3, 32) = 0.650, p = 0.589
Mandarin M2	39†	F(3, 31) = 3.618, p = 0.024*	F(1, 31) = 27.57, p < 0.001**	F(3, 31) = 1.481, p = 0.239
Mandarin M3	40	F(3, 32) = 1.905, p = 0.149	F(1, 32) = 0.262, p = 0.613	F(3, 32) = 0.635, p = 0.598
Mandarin M4	39†	F(3, 31) = 6.858, p = 0.001**	F(1, 31) = 7.528, p = 0.010*	F(3, 31) = 0.410, p = 0.747
Mandarin M5	40	F(3, 32) = 0.426, p = 0.736	F(1, 32) = 58.56, p < 0.001**	F(3, 32) = 0.370, p = 0.775
Mandarin F1	40	F(3, 32) = 1.181, p = 0.332	F(1, 32) = 41.23, p < 0.001**	F(3, 32) = 4.622, p = 0.009**
Mandarin F2	40	F(3, 32) = 3.131, p = 0.039*	F(1, 32) = 12.36, p = 0.001**	F(3, 32) = 4.043, p = 0.015*
Mandarin F3	40	F(3, 32) = 13.29, p < 0.001**	F(1, 32) = 80.40, p < 0.001**	F(3, 32) = 0.862, p = 0.471
Mandarin F4	40	F(3, 32) = 2.982, p = 0.016*	F(1, 32) = 26.65, p < 0.001**	F(3, 32) = 0.444, p = 0.723
Mandarin F5	40	F(3, 32) = 6.329, p = 0.002**	F(1, 32) = 197.8, p < 0.001**	F(3, 32) = 4.876, p = 0.007**
/u/				
Mandarin M1	40	F(3, 32) = 4.173, p = 0.013*	F(1, 32) = 0.228, p = 0.636	F(3, 32) = 0.222, p = 0.880
Mandarin M2	39†	F(3, 31) = 1.638, p = 0.201	F(1, 31) = 2.922, p = 0.097	F(3, 31) = 1.164, p = 0.339
Mandarin M3	40	F(3, 32) = 11.25, p < 0.001**	F(1, 32) = 7.133, p = 0.012*	F(3, 32) = 1.476, p = 0.240
Mandarin M4	40	F(3, 32) = 3.390, p = 0.030*	F(1, 32) = 8.107, p = 0.008**	F(3, 32) = 0.655, p = 0.586
Mandarin M5	40	F(3, 32) = 3.861, p = 0.018*	F(1, 32) = 0.822, p = 0.371	F(3, 32) = 0.501, p = 0.684
Mandarin F1	40	F(3, 32) = 27.52, p < 0.001**	F(1, 32) = 10.66, p = 0.003**	F(3, 32) = 5.009, p = 0.006**
Mandarin F2	40	F(3, 32) = 65.56, p < 0.001**	F(1, 32) = 0.005, p = 0.943	F(3, 32) = 4.037, p = 0.015*
Mandarin F3	40	F(3, 32) = 14.97, p < 0.001**	F(1, 32) = 1.515, p = 0.227	F(3, 32) = 0.665, p = 0.580
Mandarin F4	40	F(3, 32) = 1.199, p = 0.326	F(1, 32) = 1.234, p = 0.275	F(3, 32) = 1.162, p = 0.339
Mandarin F5	39†	F(3, 31) = 15.44, p < 0.001**	F(1, 31) = 20.87, p < 0.001**	F(3, 31) = 2.644, p = 0.067

*Significant at 0.05 level
**Significant at 0.005 level
†Missing data

Appendix 8

Two-way (Consonant by Task) ANOVA Results for Individual English Speakers – F2

Subject	N	Consonant Effect	Task Effect	Consonant x Task Interaction Effect
/i/				
English M	40	$F(3, 32) = 1.189, p = 0.329$	$F(1, 32) = 0.178, p = 0.676$	$F(3, 32) = 0.429, p = 0.734$
English M2	40	$F(3, 32) = 1.152, p = 0.343$	$F(1, 32) = 4.350, p = 0.045$*	$F(3, 32) = 1.659, p = 0.196$
English M3	40	$F(3, 32) = 0.666, p = 0.579$	$F(1, 32) = 0.827, p = 0.370$	$F(3, 32) = 0.232, p = 0.874$
English M4	40	$F(3, 32) = 2.964, p = 0.047$*	$F(1, 32) = 30.44, p < 0.001$**	$F(3, 32) = 1.085, p = 0.370$
English M5	40	$F(3, 32) = 2.352, p = 0.091$	$F(1, 32) = 56.56, p < 0.001$**	$F(3, 32) = 3.621, p = 0.023$*
English F1	40	$F(3, 32) = 2.456, p = 0.081$	$F(1, 32) = 25.79, p < 0.001$**	$F(3, 32) = 0.745, p = 0.533$
English F2	40	$F(3, 32) = 2.555, p = 0.073$	$F(1, 32) = 5.768, p = 0.022$*	$F(3, 32) = 0.126, p = 0.944$
English F3	40	$F(3, 32) = 1.152, p = 0.343$	$F(1, 32) = 14.62, p < 0.001$**	$F(3, 32) = 0.825, p = 0.490$
English F4	40	$F(3, 32) = 2.083, p = 0.122$	$F(1, 32) = 63.72, p < 0.001$**	$F(3, 32) = 2.267, p = 0.100$
English F5	40	$F(3, 32) = 3.191, p = 0.037$*	$F(1, 32) = 1.215, p = 0.278$	$F(3, 32) = 0.793, p = 0.507$
/a/				
English M1	60	$F(5, 48) = 3.622, p = 0.007$**	$F(1, 48) = 0.852, p = 0.361$	$F(5, 48) = 0.993, p = 0.432$
English M2	59†	$F(5, 47) = 10.17, p < 0.001$**	$F(1, 47) = 0.853, p = 0.361$	$F(5, 47) = 0.993, p = 0.432$
English M3	60	$F(5, 48) = 1.364, p = 0.254$	$F(1, 48) = 22.81, p < 0.001$**	$F(5, 48) = 0.797, p = 0.558$
English M4	60	$F(5, 48) = 6.616, p < 0.001$**	$F(1, 48) = 11.70, p = 0.001$**	$F(5, 48) = 4.827, p = 0.001$**
English M5	60	$F(5, 48) = 15.71, p < 0.001$**	$F(1, 48) = 32.45, p < 0.001$**	$F(5, 48) = 1.901, p = 0.112$
English F1	60	$F(5, 48) = 21.60, p < 0.001$**	$F(1, 48) = 5.601, p = 0.022$*	$F(5, 48) = 4.864, p = 0.001$**
English F2	60	$F(5, 48) = 3.466, p = 0.009$**	$F(1, 48) = 4.431, p = 0.041$*	$F(5, 48) = 0.802, p = 0.554$
English F3	59†	$F(5, 47) = 2.040, p = 0.090$	$F(1, 47) = 20.25, p < 0.001$**	$F(5, 47) = 2.831, p = 0.026$*
English F41	60	$F(5, 48) = 1.961, p = 0.102$	$F(1, 48) = 68.89, p < 0.001$**	$F(5, 48) = 0.495, p = 0.779$
English F5	60	$F(5, 48) = 1.617, p = 0.174$	$F(1, 48) = 10.51, p = 0.002$**	$F(5, 48) = 1.202, p = 0.323$
/u/				
English M1	40	$F(3, 32) = 5.828, p = 0.003$**	$F(1, 32) = 71.69, p < 0.001$**	$F(3, 32) = 1.096, p = 0.365$
English M2	40	$F(3, 32) = 20.87, p < 0.001$**	$F(1, 32) = 2.758, p = 0.107$	$F(3, 32) = 0.995, p = 0.408$
English M3	39†	$F(3, 31) = 3.484, p = 0.027$*	$F(1, 31) = 1.565, p = 0.220$	$F(3, 31) = 1.334, p = 0.281$
English M4	40	$F(3, 32) = 3.042, p = 0.043$*	$F(1, 32) = 8.456, p = 0.007$**	$F(3, 32) = 1.360, p = 0.273$
English M5	38†	$F(3, 30) = 5.866, p = 0.003$**	$F(1, 30) = 8.256, p = 0.007$**	$F(3, 30) = 0.933, p = 0.437$
English F1	40	$F(3, 32) = 4.942, p = 0.006$**	$F(1, 32) = 5.982, p = 0.020$*	$F(3, 32) = 2.880, p = 0.051$
English F2	40	$F(3, 32) = 0.252, p = 0.859$	$F(1, 32) = 0.224, p = 0.639$	$F(3, 32) = 1.949, p = 0.142$
English F3	40	$F(3, 32) = 5.139, p = 0.005$**	$F(1, 32) = 36.02, p < 0.001$**	$F(3, 32) = 1.801, p = 0.167$
English F4	40	$F(3, 32) = 15.86, p < 0.001$**	$F(1, 32) = 13.92, p < 0.001$**	$F(3, 32) = 0.408, p = 0.748$
English F5	38†	$F(3, 30) = 47.63, p < 0.001$**	$F(1, 30) = 5.035, p = 0.032$*	$F(3, 30) = 0.320, p = 0.811$

*Significant at 0.05 level
**Significant at 0.005 level
†Missing data

Appendix 9

Two-way (Consonant by Task) ANOVA Results for Individual Mandarin Speakers – F2

Subject	N	Consonant Effect	Task Effect	Consonant x Task Interaction Effect
/i/				
Mandarin M1	50	F(4, 40) = 2.257, p = 0.080	F(1, 40) = 1.168, p = 0.286	F(4, 40) = 1.308, p = 0.283
Mandarin M2	49†	F(4, 39) = 3.512, p = 0.015*	F(1, 39) = 2.640, p = 0.112	F(4, 39) = 0.951, p = 0.445
Mandarin M3	50	F(4, 40) = 0.451, p = 0.771	F(1, 40) = 0.478, p = 0.493	F(4, 40) = 0.888, p = 0.480
Mandarin M4	50	F(4, 40) = 3.467, p = 0.016*	F(1, 40) = 0.239, p = 0.627	F(4, 40) = 0.468, p = 0.759
Mandarin M5	50	F(4, 40) = 0.393, p = 0.812	F(1, 40) = 0.032, p = 0.859	F(4, 40) = 0.600, p = 0.665
Mandarin F1	50	F(4, 40) = 3.075, p = 0.027*	F(1, 40) = 103.4, p < 0.001**	F(4, 40) = 0.282, p = 0.888
Mandarin F2	49†	F(4, 39) = 2.165, p = 0.091	F(1, 39) = 31.14, p < 0.001**	F(4, 39) = 1.888, p = 0.132
Mandarin F3	49†	F(4, 39) = 1.077, p = 0.381	F(1, 39) = 42.43, p < 0.001**	F(4, 39) = 0.413, p = 0.798
Mandarin F4	50	F(4, 40) = 1.746, p = 0.159	F(1, 40) = 1.194, p = 0.281	F(4, 40) = 0.350, p = 0.843
Mandarin F5	50	F(4, 40) = 3.761, p = 0.011*	F(1, 40) = 3.692, p = 0.062	F(4, 40) = 1.317, p = 0.280
/a/				
Mandarin M1	70	F(6, 56) = 1.088, p = 0.381	F(1, 56) = 0.035, p = 0.853	F(6, 56) = 0.990, p = 0.441
Mandarin M2	68†	F(6, 54) = 3.246, p = 0.008**	F(1, 54) = 13.47, p < 0.001**	F(6, 54) = 1.193, p = 0.324
Mandarin M3	69†	F(6, 55) = 5.060, p < 0.001**	F(1, 55) = 8.011, p = 0.006**	F(6, 55) = 0.966, p = 0.456
Mandarin M4	69†	F(6, 55) = 2.242, p = 0.052	F(1, 55) = 15.71, p < 0.001**	F(6, 55) = 0.908, p = 0.496
Mandarin M5	70	F(6, 56) = 1.082, p = 0.384	F(1, 56) = 1.666, p = 0.202	F(6, 56) = 0.717, p = 0.638
Mandarin F1	69†	F(6, 55) = 3.894, p = 0.003**	F(1, 55) = 16.68, p < 0.001**	F(6, 55) = 0.905, p = 0.498
Mandarin F2	70	F(6, 56) = 0.810, p = 0.567	F(1, 56) = 1.782, p = 0.187	F(6, 56) = 0.585, p = 0.741
Mandarin F3	70	F(6, 56) = 0.916, p = 0.491	F(1, 56) = 3.372, p = 0.072	F(6, 56) = 0.560, p = 0.760
Mandarin F4	70	F(6, 56) = 0.746, p = 0.615	F(1, 56) = 3.425, p = 0.070	F(6, 56) = 1.465, p = 0.207
Mandarin F5	70	F(6, 56) = 4.423, p < 0.001**	F(1, 56) = 1.285, p = 0.262	F(6, 56) = 0.195, p = 0.977
/u/				
Mandarin M1	50	F(4, 40) = 7.244, p < 0.001**	F(1, 40) = 9.660, p = 0.003**	F(4, 40) = 1.118, p = 0.362
Mandarin M2	50	F(4, 40) = 8.183, p < 0.001**	F(1, 40) = 36.35, p < 0.001**	F(4, 40) = 0.655, p = 0.627
Mandarin M3	50	F(4, 40) = 3.717, p = 0.012*	F(1, 40) = 9.602, p = 0.004**	F(4, 40) = 2.060, p = 0.104
Mandarin M4	50	F(4, 40) = 1.107, p = 0.366	F(1, 40) = 0.905, p = 0.347	F(4, 40) = 2.220, p = 0.084
Mandarin M5	50	F(4, 40) = 3.945, p = 0.009**	F(1, 40) = 54.55, p < 0.001**	F(4, 40) = 1.941, p = 0.122
Mandarin F1	50	F(4, 40) = 1.892, p = 0.131	F(1, 40) = 0.534, p = 0.469	F(4, 40) = 0.539, p = 0.708
Mandarin F2	50	F(4, 40) = 0.822, p = 0.519	F(1, 40) = 0.051, p = 0.823	F(4, 40) = 1.330, p = 0.275
Mandarin F3	50	F(4, 40) = 6.177, p < 0.001**	F(1, 40) = 20.09, p < 0.001**	F(4, 40) = 3.117, p = 0.025*
Mandarin F4	50	F(4, 40) = 0.110, p = 0.978	F(1, 40) = 0.348, p = 0.559	F(4, 40) = 1.083, p = 0.378
Mandarin F5	50	F(4, 40) = 3.956, p = 0.008**	F(1, 40) = 0.294, p = 0.591	F(4, 40) = 4.599, p = 0.004**

*Significant at 0.05 level
**Significant at 0.005 level
†Missing data

Appendix 10

Two-way (Tone by Task) ANOVA Results for Individual Mandarin Speakers – F2

Subject	N	Tone Effect	Task Effect	Tone x Task Interaction Effect
/i/				
Mandarin M1	40	$F(3, 32) = 2.816, p = 0.055$	$F(1, 32) = 1.449, p = 0.238$	$F(3, 32) = 0.563, p = 0.643$
Mandarin M2	40	$F(3, 32) = 1.241, p = 0.311$	$F(1, 32) = 7.035, p = 0.012$*	$F(3, 32) = 1.487, p = 0.237$
Mandarin M3	40	$F(3, 32) = 2.400, p = 0.086$	$F(1, 32) = 8.291, p = 0.007$**	$F(3, 32) = 0.066, p = 0.977$
Mandarin M4	40	$F(3, 32) = 1.937, p = 0.143$	$F(1, 32) = 0.994, p = 0.326$	$F(3, 32) = 2.258, p = 0.101$
Mandarin M5	40	$F(3, 32) = 0.708, p = 0.554$	$F(1, 32) = 0.136, p = 0.715$	$F(3, 32) = 0.913, p = 0.446$
Mandarin F1	40	$F(3, 32) = 0.862, p = 0.471$	$F(1, 32) = 0.019, p = 0.892$	$F(3, 32) = 1.177, p = 0.334$
Mandarin F2	40	$F(3, 32) = 0.473, p = 0.703$	$F(1, 32) = 1.519, p = 0.227$	$F(3, 32) = 1.612, p = 0.206$
Mandarin F3	40	$F(3, 32) = 0.461, p = 0.711$	$F(1, 32) = 18.23, p < 0.001$**	$F(3, 32) = 0.187, p = 0.905$
Mandarin F4	40	$F(3, 32) = 1.394, p = 0.263$	$F(1, 32) = 4.410, p = 0.044$*	$F(3, 32) = 0.465, p = 0.709$
Mandarin F5	40	$F(3, 32) = 5.592, p = 0.003$**	$F(1, 32) = 0.084, p = 0.774$	$F(3, 32) = 1.177, p = 0.334$
/a/				
Mandarin M1	40	$F(3, 32) = 0.639, p = 0.595$	$F(1, 32) = 0.170, p = 0.083$	$F(3, 32) = 1.042, p = 0.387$
Mandarin M2	$39^{\dagger}$	$F(3, 31) = 10.45, p < 0.001$**	$F(1, 31) = 2.919, p = 0.098$	$F(3, 31) = 1.489, p = 0.237$
Mandarin M3	40	$F(3, 32) = 0.494, p = 0.689$	$F(1, 32) = 0.236, p = 0.631$	$F(3, 32) = 1.705, p = 0.186$
Mandarin M4	$39^{\dagger}$	$F(3, 31) = 0.466, p = 0.708$	$F(1, 31) = 15.17, p < 0.001$**	$F(3, 31) = 0.654, p = 0.586$
Mandarin M5	40	$F(3, 32) = 1.426, p = 0.253$	$F(1, 32) = 26.98, p < 0.001$**	$F(3, 32) = 0.927, p = 0.439$
Mandarin F1	40	$F(3, 32) = 16.59, p < 0.001$**	$F(1, 32) = 9.401, p = 0.004$**	$F(3, 32) = 3.425, p = 0.029$*
Mandarin F2	40	$F(3, 32) = 1.634, p = 0.201$	$F(1, 32) = 3.834, p = 0.059$	$F(3, 32) = 0.007, p = 0.999$
Mandarin F3	40	$F(3, 32) = 6.836, p = 0.001$**	$F(1, 32) = 3.197, p = 0.083$	$F(3, 32) = 1.781, p = 0.171$
Mandarin F4	40	$F(3, 32) = 1.698, p = 0.187$	$F(1, 32) = 0.119, p = 0.732$	$F(3, 32) = 3.124, p = 0.039$*
Mandarin F5	40	$F(3, 32) = 15.18, p < 0.001$**	$F(1, 32) = 0.348, p = 0.559$	$F(3, 32) = 0.062, p = 0.979$
/u/				
Mandarin M1	40	$F(3, 32) = 6.724, p = 0.001$**	$F(1, 32) = 0.843, p = 0.365$	$F(3, 32) = 1.138, p = 0.348$
Mandarin M2	$39^{\dagger}$	$F(3, 31) = 7.141, p < 0.001$**	$F(1, 31) = 20.79, p < 0.001$**	$F(3, 31) = 3.585, p = 0.025$*
Mandarin M3	40	$F(3, 32) = 4.428, p = 0.010$*	$F(1, 32) = 0.988, p = 0.328$	$F(3, 32) = 3.326, p = 0.032$*
Mandarin M4	40	$F(3, 32) = 33.29, p < 0.001$**	$F(1, 32) = 0.378, p = 0.543$	$F(3, 32) = 0.250, p = 0.861$
Mandarin M5	40	$F(3, 32) = 13.14, p < 0.001$**	$F(1, 32) = 2.935, p = 0.096$	$F(3, 32) = 2.326, p = 0.093$
Mandarin F1	40	$F(3, 32) = 6.803, p = 0.001$**	$F(1, 32) = 2.835, p = 0.102$	$F(3, 32) = 0.265, p = 0.850$
Mandarin F2	40	$F(3, 32) = 9.391, p < 0.001$**	$F(1, 32) = 14.22, p < 0.001$**	$F(3, 32) = 0.577, p = 0.635$
Mandarin F3	40	$F(3, 32) = 11.99, p < 0.001$**	$F(1, 32) = 12.24, p = 0.001$**	$F(3, 32) = 2.332, p = 0.093$
Mandarin F4	40	$F(3, 32) = 3.800, p = 0.019$*	$F(1, 32) = 0.026, p = 0.873$	$F(3, 32) = 0.778, p = 0.515$
Mandarin F5	$39^{\dagger}$	$F(3, 31) = 4.575, p = 0.009$**	$F(1, 31) = 0.496, p = 0.486$	$F(3, 31) = 2.338, p = 0.093$

*Significant at 0.05 level
**Significant at 0.005 level
†Missing data

Appendix 11

Two-way (Consonant by Task) ANOVA Results for Individual English Speakers – F0

Subject	N	Consonant Effect	Task Effect	Consonant x Task Interaction Effect
/i/				
English M1	40	$F(3, 32) = 2.264, p = 0.100$	$F(1, 32) = 4.406, p = 0.044$*	$F(3, 32) = 1.796, p = 0.168$
English M2	40	$F(3, 32) = 0.556, p = 0.648$	$F(1, 32) = 51.40, p < 0.001$**	$F(3, 32) = 0.702, p = 0.558$
English M3	40	$F(3, 32) = 2.606, p = 0.069$	$F(1, 32) = 0.002, p = 0.962$	$F(3, 32) = 1.233, p = 0.314$
English M4	40	$F(3, 32) = 1.336, p = 0.280$	$F(1, 32) = 14.00, p < 0.001$**	$F(3, 32) = 2.679, p = 0.064$
English M5	40	$F(3, 32) = 1.058, p = 0.381$	$F(1, 32) = 0.311, p = 0.581$	$F(3, 32) = 0.434, p = 0.730$
English F1	40	$F(3, 32) = 1.765, p = 0.174$	$F(1, 32) = 31.01, p < 0.001$**	$F(3, 32) = 1.006, p = 0.403$
English F2	40	$F(3, 32) = 2.034, p = 0.129$	$F(1, 32) = 1.718, p = 0.199$	$F(3, 32) = 1.562, p = 0.218$
English F3	40	$F(3, 32) = 2.904, p = 0.050$	$F(1, 32) = 4.762, p = 0.037$*	$F(3, 32) = 2.160, p = 0.112$
English F4	40	$F(3, 32) = 0.304, p = 0.822$	$F(1, 32) = 9.193, p = 0.005$**	$F(3, 32) = 2.468, p = 0.080$
English F5	40	$F(3, 32) = 1.013, p = 0.400$	$F(1, 32) = 0.165, p = 0.687$	$F(3, 32) = 0.078, p = 0.971$
/a/				
English M1	60	$F(5, 48) = 0.666, p = 0.651$	$F(1, 48) = 16.16, p < 0.001$**	$F(5, 48) = 0.783, p = 0.567$
English M2	59†	$F(5, 47) = 3.655, p = 0.007$**	$F(1, 47) = 15.63, p < 0.001$**	$F(5, 47) = 1.997, p = 0.096$
English M3	60	$F(5, 48) = 2.017, p = 0.093$	$F(1, 48) = 0.299, p = 0.587$	$F(5, 48) = 1.685, p = 0.156$
English M4	60	$F(5, 48) = 1.116, p = 0.364$	$F(1, 48) = 0.029, p = 0.865$	$F(5, 48) = 0.530, p = 0.753$
English M5	60	$F(5, 48) = 0.917, p = 0.478$	$F(1, 48) = 0.250, p = 0.619$	$F(5, 48) = 0.794, p = 0.559$
English F1	60	$F(5, 48) = 0.392, p = 0.852$	$F(1, 48) = 43.08, p < 0.001$**	$F(5, 48) = 1.123, p = 0.361$
English F2	60	$F(5, 48) = 1.896, p = 0.113$	$F(1, 48) = 0.302, p = 0.585$	$F(5, 48) = 1.485, p = 0.212$
English F3	59†	$F(5, 47) = 2.213, p = 0.069$	$F(1, 47) = 0.057, p = 0.813$	$F(5, 47) = 0.662, p = 0.654$
English F4	60	$F(5, 48) = 1.244, p = 0.304$	$F(1, 48) = 4.798, p = 0.033$*	$F(5, 48) = 1.183, p = 0.331$
English F5	60	$F(5, 48) = 1.042, p = 0.404$	$F(1, 48) = 3.364, p = 0.073$	$F(5, 48) = 0.537, p = 0.748$
/u/				
English M1	40	$F(3, 32) = 0.808, p = 0.499$	$F(1, 32) = 19.41, p < 0.001$**	$F(3, 32) = 0.312, p = 0.816$
English M2	40	$F(3, 32) = 4.113, p = 0.014$*	$F(1, 32) = 89.39, p < 0.001$**	$F(3, 32) = 6.942, p < 0.001$**
English M3	39†	$F(3, 31) = 3.364, p = 0.031$*	$F(1, 31) = 3.628, p = 0.066$	$F(3, 31) = 1.041, p = 0.388$
English M4	40	$F(3, 32) = 7.314, p < 0.001$**	$F(1, 32) = 2.419, p = 0.130$	$F(3, 32) = 0.019, p = 0.996$
English M5	38†	$F(3, 30) = 2.004, p = 0.135$	$F(1, 30) = 0.320, p = 0.576$	$F(3, 30) = 0.506, p = 0.681$
English F1	40	$F(3, 32) = 1.514, p = 0.230$	$F(1, 32) = 186.1, p < 0.001$**	$F(3, 32) = 0.239, p = 0.869$
English F2	40	$F(3, 32) = 0.098, p = 0.961$	$F(1, 32) = 12.99, p = 0.001$**	$F(3, 32) = 0.180, p = 0.909$
English F3	40	$F(3, 32) = 0.234, p = 0.872$	$F(1, 32) = 0.649, p = 0.426$	$F(3, 32) = 0.306, p = 0.821$
English F4	40	$F(3, 32) = 0.440, p = 0.726$	$F(1, 32) = 16.53, p < 0.001$**	$F(3, 32) = 2.044, p = 0.127$
English F5	38†	$F(3, 30) = 2.085, p = 0.123$	$F(1, 30) = 3.582, p = 0.068$	$F(3, 30) = 0.118, p = 0.949$

*Significant at 0.05 level
**Significant at 0.005 level
†Missing data

Appendix 12

Two-way (Consonant by Task) ANOVA Results for Individual Mandarin Speakers – F0

Subject	N	Consonant Effect	Task Effect	Consonant x Task Interaction Effect
/i/				
Mandarin M	50	$F(4, 40) = 0.583, p = 0.677$	$F(1, 40) = 0.019, p = 0.890$	$F(4, 40) = 0.507, p = 0.731$
Mandarin M2	49†	$F(4,39) = 1.673, p = 0.176$	$F(1, 39) = 29.98, p < 0.001$**	$F(4, 39) = 1.855, p = 0.138$
Mandarin M3	50	$F(4,40) = 0.738, p = 0.571$	$F(1, 40) = 9.871, p = 0.003$**	$F(4, 40) = 0.949, p = 0.446$
Mandarin M4	50	$F(4,40) = 0.686, p = 0.606$	$F(1, 40) = 19.03, p < 0.001$**	$F(4, 40) = 5.433, p = 0.001$**
Mandarin M5	50	$F(4,40) = 1.120, p = 0.361$	$F(1, 40) = 5.578, p = 0.023$*	$F(4, 40) = 1.145, p = 0.350$
Mandarin F1	50	$F(4,40) = 6.383, p < 0.001$**	$F(1, 40) = 4.943, p = 0.032$*	$F(4, 40) = 1.491, p = 0.223$
Mandarin F2	49†	$F(4,39) = 0.743, p = 0.569$	$F(1, 39) = 36.97, p < 0.001$**	$F(4, 39) = 1.414, p = 0.248$
Mandarin F3	49†	$F(4,39) = 1.404, p = 0.251$	$F(1, 39) = 4.478, p = 0.041$*	$F(4, 39) = 0.340, p = 0.850$
Mandarin F4	50	$F(4,40) = 3.243, p = 0.021$*	$F(1, 40) = 70.51, p < 0.001$**	$F(4, 40) = 0.157, p = 0.959$
Mandarin F5	50	$F(4,40) = 2.231, p = 0.083$	$F(1, 40) =64.264, p < 0.001$**	$F(4, 40) = 0.621, p = 0.650$
/a/				
Mandarin M1	70	$F(6, 56) = 0.713, p = 0.641$	$F(1, 56) = 0.852, p = 0.360$	$F(6, 56) = 0.387, p = 0.885$
Mandarin M2	68†	$F(6, 54) = 0.761, p = 0.604$	$F(1, 54) = 49.32, p < 0.001$**	$F(6, 54) = 0.674, p = 0.671$
Mandarin M3	69†	$F(6, 55) = 0.366, p = 0.897$	$F(1, 55) = 9.955, p= 0.003$**	$F(6, 55) = 0.168, p = 0.984$
Mandarin M4	69†	$F(6, 55) = 0.754, p = 0.609$	$F(1, 55) = 0.089, p = 0.767$	$F(6, 55) = 0.489, p = 0.814$
Mandarin M5	70	$F(6, 56) = 0.464, p = 0.832$	$F(1, 56) = 11.04, p = 0.002$**	$F(6, 56) = 0.916, p = 0.490$
Mandarin F1	69†	$F(6, 55) = 3.965, p = 0.002$**	$F(1, 55) = 24.80, p < 0.001$**	$F(6, 55) = 1.002, p = 0.433$
Mandarin F2	70	$F(6, 56) = 0.374, p = 0.893$	$F(1, 56) = 23.44, p < 0.001$**	$F(6, 56) = 0.147, p = 0.989$
Mandarin F3	70	$F(6, 56) = 2.267, p = 0.050$	$F(1, 56) = 7.119, p = 0.010$*	$F(6, 56) = 0.952, p = 0.466$
Mandarin F4	70	$F(6, 56) = 0.751, p = 0.611$	$F(1, 56) = 1.382, p = 0.245$	$F(6, 56) = 0.330, p = 0.918$
Mandarin F5	70	$F(6, 56) = 0.439, p = 0.850$	$F(1, 56) = 43.07, p < 0.001$**	$F(6, 56) = 0.459, p = 0.836$
/u/				
Mandarin M1	50	$F(4, 40) = 1.078, p = 0.380$	$F(1, 40) = 4.823, p = 0.034$*	$F(4, 40) = 0.784, p = 0.542$
Mandarin M2	50	$F(4, 40) = 0.786, p = 0.541$	$F(1, 40) = 62.81, p < 0.001$**	$F(4, 40) = 0.541, p = 0.706$
Mandarin M3	50	$F(4, 40) = 0.707, p = 0.592$	$F(1, 40) = 12.06, p = 0.001$**	$F(4, 40) = 0.298, p = 0.877$
Mandarin M4	50	$F(4, 40) = 1.670, p = 0.176$	$F(1, 40) = 11.37, p = 0.002$**	$F(4, 40) = 0.209, p = 0.932$
Mandarin M5	50	$F(4, 40) = 0.236, p = 0.917$	$F(1, 40) = 7.954, p = 0.007$**	$F(4, 40) = 0.658, p = 0.625$
Mandarin F1	50	$F(4, 40) = 2.302, p = 0.075$	$F(1, 40) = 8.021, p = 0.007$**	$F(4, 40) = 0.298, p = 0.878$
Mandarin F2	50	$F(4, 40) = 0.214, p = 0.929$	$F(1, 40) = 13.86, p < 0.001$**	$F(4, 40) = 0.309, p = 0.870$
Mandarin F3	50	$F(4, 40) = 1.703, p = 0.168$	$F(1, 40) = 3.881, p = 0.056$	$F(4, 40) = 1.372, p = 0.261$
Mandarin F4	50	$F(4, 40) = 0.967, p = 0.436$	$F(1, 40) = 57.07, p < 0.001$**	$F(4, 40) = 0.841, p = 0.508$
Mandarin F5	50	$F(4, 40) = 1.313, p = 0.282$	$F(1, 40) = 58.52, p < 0.001$**	$F(4, 40) = 0.131, p = 0.970$

*Significant at 0.05 level
**Significant at 0.005 level
†Missing data

Appendix 13

Two-way (Tone by Task) ANOVA Results for Individual Mandarin Speakers – F0

Subject	N	Tone Effect	Task Effect	Tone x Task Interaction Effect
/i/				
Mandarin M1	40	$F(3, 32) = 60.00, p < 0.001$**	$F(1, 32) = 1.762, p = 0.194$	$F(3, 32) = 0.048, p = 0.986$
Mandarin M2	40	$F(3, 32) = 57.94, p < 0.001$**	$F(1, 32) = 20.611, p < 0.001$**	$F(3, 32) = 2.275, p = 0.099$
Mandarin M3	40	$F(3, 32) = 25.65, p < 0.001$**	$F(1, 32) = 0.356, p = 0.135$	$F(3, 32) = 0.380, p = 0.768$
Mandarin M4	40	$F(3, 32) = 17.43, p < 0.001$**	$F(1, 32) = 0.120, p = 0.731$	$F(3, 32) = 17.65, p < 0.001$**
Mandarin M5	40	$F(3, 32) = 6.871, p = 0.001$**	$F(1, 32) = 0.078, p = 0.782$	$F(3, 32) = 1.387, p = 0.265$
Mandarin F1	40	$F(3, 32) = 52.51, p < 0.001$**	$F(1, 32) = 3.126, p = 0.087$	$F(3, 32) = 2.516, p = 0.076$
Mandarin F2	40	$F(3, 32) = 36.32, p < 0.001$**	$F(1, 32) = 10.61, p = 0.003$**	$F(3, 32) = 1.536, p = 0.224$
Mandarin F3	40	$F(3, 32) = 45.89, p < 0.001$**	$F(1, 32) = 1.369, p = 0.251$	$F(3, 32) = 1.153, p = 0.343$
Mandarin F4	40	$F(3, 32) = 28.84, p < 0.001$**	$F(1, 32) = 0.375, p = 0.545$	$F(3, 32) = 2.042, p = 0.128$
Mandarin F5	40	$F(3, 32) = 31.88, p < 0.001$**	$F(1, 32) = 8.883, p = 0.005$**	$F(3, 32) = 4.069, p = 0.015$*
/a/				
Mandarin M1	40	$F(3, 32) = 63.84, p < 0.001$**	$F(1, 32) = 1.570, p = 0.219$	$F(3, 32) = 0.443, p = 0.724$
Mandarin M2	39†	$F(3, 31) = 24.38, p < 0.001$**	$F(1, 31) = 26.02, p < 0.001$**	$F(3, 31) = 1.630, p = 0.203$
Mandarin M3	40	$F(3, 32) = 29.91, p < 0.001$**	$F(1, 32) = 0.067, p = 0.798$	$F(3, 32) = 1.155, p = 0.342$
Mandarin M4	39†	$F(3, 31) = 84.69, p < 0.001$**	$F(1, 31) = 5.939, p = 0.021$*	$F(3, 31) = 0.082, p = 0.969$
Mandarin M5	40	$F(3, 32) = 34.20, p < 0.001$**	$F(1, 32) = 0.426, p = 0.519$	$F(3, 32) = 0.720, p = 0.547$
Mandarin F1	40	$F(3, 32) = 93.93, p < 0.001$**	$F(1, 32) = 0.855, p = 0.362$	$F(3, 32) = 2.347, p = 0.091$
Mandarin F2	40	$F(3, 32) = 7.839, p < 0.001$**	$F(1, 32) = 0.843, p = 0.365$	$F(3, 32) = 2.250, p = 0.101$
Mandarin F3	40	$F(3, 32) = 42.28, p < 0.001$**	$F(1, 32) = 0.517, p = 0.477$	$F(3, 32) = 3.544, p = 0.025$*
Mandarin F4	40	$F(3, 32) = 5.212, p = 0.005$**	$F(1, 32) = 3.905, p = 0.057$	$F(3, 32) = 1.187, p = 0.330$
Mandarin F5	40	$F(3, 32) = 76.62, p < 0.001$**	$F(1, 32) = 14.19, p < 0.001$**	$F(3, 32) = 1.680, p = 0.191$
/u/				
Mandarin M1	40	$F(3, 32) = 44.780, p < 0.001$**	$F(1, 32) = 0.159, p = 0.693$	$F(3, 32) = 0.690, p = 0.565$
Mandarin M2	39†	$F(3, 31) = 35.009, p < 0.001$**	$F(1, 31) = 18.04, p < 0.001$**	$F(3, 31) = 0.506, p = 0.681$
Mandarin M3	40	$F(3, 32) = 25.882, p < 0.001$**	$F(1, 32) = 5.100, p = 0.031$*	$F(3, 32) = 0.867, p = 0.468$
Mandarin M4	40	$F(3, 32) = 11.695, p < 0.001$**	$F(1, 32) = 0.581, p = 0.452$	$F(3, 32) = 1.042, p = 0.387$
Mandarin M5	40	$F(3, 32) = 13.861, p < 0.001$**	$F(1, 32) = 3.429, p = 0.073$	$F(3, 32) = 0.682, p = 0.570$
Mandarin F1	40	$F(3, 32) = 26.159, p < 0.001$**	$F(1, 32) = 1.397, p = 0.246$	$F(3, 32) = 0.537, p = 0.660$
Mandarin F2	40	$F(3, 32) = 20.805, p < 0.001$**	$F(1, 32) = 0.031, p = 0.860$	$F(3, 32) = 0.435, p = 0.730$
Mandarin F3	40	$F(3, 32) = 10.148, p < 0.001$**	$F(1, 32) = 7.643, p = 0.009$**	$F(3, 32) = 3.992, p = 0.016$*
Mandarin F4	40	$F(3, 32) = 36.908, p < 0.001$**	$F(1, 32) = 4.326, p = 0.046$*	$F(3, 32) = 0.091, p = 0.965$
Mandarin F5	39†	$F(3, 31) = 61.808, p < 0.001$**	$F(1, 31) = 16.83, p < 0.001$**	$F(3, 31) = 2.508, p = 0.077$

*Significant at 0.05 level
**Significant at 0.005 level
†Missing data

Appendix 14

Two-way (Consonant by Task) ANOVA Results for Individual English Speakers – %jitter

Subject	N	Consonant Effect	Task Effect	Consonant x Task Interaction Effect
/i/				
English M1	40	$F(3, 32) = 0.640, p = 0.595$	$F(1, 32) = 0.029, p = 0.866$	$F(3, 32) = 2.448, p = 0.082$
English M2	40	$F(3, 32) = 4.793, p = 0.007$**	$F(1, 32) = 7.968, p = 0.008$**	$F(3, 32) = 0.163, p = 0.920$
English M3	40	$F(3, 32) = 0.244, p = 0.865$	$F(1, 32) = 4.934, p = 0.034$*	$F(3, 32) = 0.162, p = 0.921$
English M4	40	$F(3, 32) = 1.687, p = 0.189$	$F(1, 32) = 13.53, p < 0.001$**	$F(3, 32) = 1.927, p = 0.145$
English M5	40	$F(3, 32) = 0.200, p = 0.896$	$F(1, 32) = 0.818, p = 0.373$	$F(3, 32) = 0.626, p = 0.603$
English F1	40	$F(3, 32) = 1.078, p = 0.372$	$F(1, 32) = 36.48, p < 0.001$**	$F(3, 32) = 2.048, p = 0.127$
English F2	40	$F(3, 32) = 1.930, p = 0.145$	$F(1, 32) = 0.338, p = 0.565$	$F(3, 32) = 1.402, p = 0.260$
English F3	40	$F(3, 32) = 4.858, p = 0.007$**	$F(1, 32) = 43.30, p < 0.001$**	$F(3, 32) = 1.415, p = 0.256$
English F4	40	$F(3, 32) = 0.918, p = 0.443$	$F(1, 32) = 2.099, p = 0.157$	$F(3, 32) = 1.216, p = 0.320$
English F5	40	$F(3, 32) = 0.048, p = 0.986$	$F(1, 32) = 0.025, p = 0.876$	$F(3, 32) = 0.844, p = 0.480$
/a/				
English M1	60	$F(5, 48) = 1.849, p = 0.121$	$F(1, 48) = 6.9860, p = 0.011$*	$F(5, 48) = 2.902, p = 0.023$*
English M2	59†	$F(5, 47) = 1.855, p = 0.120$	$F(1, 47) = 6.3150, p = 0.015$*	$F(5, 47) = 1.591, p = 0.181$
English M3	60	$F(5, 48) = 0.503, p = 0.772$	$F(1, 48) = 12.236, p = 0.001$**	$F(5, 48) = 0.346, p = 0.882$
English M4	60	$F(5, 48) = 1.317, p = 0.273$	$F(1, 48) = 0.0132, p = 0.909$	$F(5, 48) = 1.043, p = 0.403$
English M5	60	$F(5, 48) = 0.082, p = 0.995$	$F(1, 48) = 13.125, p < 0.001$**	$F(5, 48) = 1.193, p = 0.327$
English F1	60	$F(5, 48) = 0.447, p = 0.813$	$F(1, 48) = 38.758, p < 0.001$**	$F(5, 48) = 0.444, p = 0.815$
English F2	60	$F(5, 48) = 0.948, p = 0.459$	$F(1, 48) = 0.0076, p = 0.931$	$F(5, 48) = 0.822, p = 0.540$
English F3	59†	$F(5, 47) = 0.554, p = 0.734$	$F(1, 47) = 26.483, p < 0.001$**	$F(5, 47) = 0.473, p = 0.795$
English F4	60	$F(5, 48) = 0.389, p = 0.854$	$F(1, 48) = 1.0680, p = 0.306$	$F(5, 48) = 0.804, p = 0.553$
English F5	60	$F(5, 48) = 0.471, p = 0.796$	$F(1, 48) = 9.3330, p = 0.004$**	$F(5, 48) = 1.313, p = 0.274$
/u/				
English M1	40	$F(3, 32) = 0.566, p = 0.641$	$F(1, 32) = 0.2730, p = 0.605$	$F(3, 32) = 1.176, p = 0.334$
English M2	40	$F(3, 32) = 8.821, p < 0.001$**	$F(1, 32) = 45.180, p < 0.001$**	$F(3, 32) = 0.627, p = 0.603$
English M3	39†	$F(3, 31) = 1.962, p = 0.140$	$F(1, 31) = 1.5780, p = 0.218$	$F(3, 31) = 0.332, p = 0.802$
English M4	40	$F(3, 32) = 0.948, p = 0.429$	$F(1, 32) = 17.998, p < 0.001$**	$F(3, 32) = 0.710, p = 0.553$
English M5	38†	$F(3, 30) = 3.340, p = 0.032$*	$F(1, 30) = 0.0057, p = 0.940$	$F(3, 30) = 1.292, p = 0.295$
English F1	40	$F(3, 32) = 1.384, p = 0.265$	$F(1, 32) = 50.749, p < 0.001$**	$F(3, 32) = 0.157, p = 0.924$
English F2	40	$F(3, 32) = 1.704, p = 0.186$	$F(1, 32) = 0.6130, p = 0.439$	$F(3, 32) = 0.346, p = 0.792$
English F3	40	$F(3, 32) = 2.034, p = 0.129$	$F(1, 32) = 35.190, p < 0.001$**	$F(3, 32) = 2.069, p = 0.124$
English F4	40	$F(3, 32) = 2.975, p = 0.046$*	$F(1, 32) = 0.0567, p = 0.813$	$F(3, 32) = 1.481, p = 0.238$
English F5	38†	$F(3, 30) = 0.838, p = 0.484$	$F(1, 30) = 5.5440, p = 0.025$*	$F(3, 30) = 0.718, p = 0.549$

*Significant at 0.05 level
**Significant at 0.005 level
†Missing data

Appendix 15

Two-way (Consonant by Task) ANOVA Results for Individual Mandarin Speakers – %jitter

Subject	N	Consonant Effect	Task Effect	Consonant x Task Interaction Effect
/i/				
Mandarin M1	50	$F(4, 40) = 1.382, p = 0.257$	$F(1, 40) = 2.578, p = 0.116$	$F(4, 40) = 1.984, p = 0.116$
Mandarin M2	49†	$F(4, 39) = 2.746, p = 0.042$*	$F(1, 39) = 2.671, p = 0.110$	$F(4, 39) = 1.462, p = 0.232$
Mandarin M3	50	$F(4, 40) = 1.122, p = 0.360$	$F(1, 40) = 1.027, p = 0.317$	$F(4, 40) = 0.956, p = 0.442$
Mandarin M4	50	$F(4, 40) = 0.346, p = 0.845$	$F(1, 40) = 0.442, p = 0.510$	$F(4, 40) = 0.766, p = 0.554$
Mandarin M5	50	$F(4, 40) = 0.632, p = 0.643$	$F(1, 40) = 41.459, p < 0.001$**	$F(4, 40) = 0.752, p = 0.562$
Mandarin F1	50	$F(4, 40) = 0.236, p = 0.916$	$F(1, 40) = 9.449, p = 0.004$**	$F(4, 40) = 0.617, p = 0.653$
Mandarin F2	49†	$F(4, 39) = 0.404, p = 0.804$	$F(1, 39) = 0.971, p = 0.330$	$F(4, 39) = 0.549, p = 0.701$
Mandarin F3	49†	$F(4, 39) = 0.541, p = 0.707$	$F(1, 39) = 6.556, p = 0.014$*	$F(4, 39) = 0.481, p = 0.750$
Mandarin F4	50	$F(4, 40) = 0.487, p = 0.746$	$F(1, 40) = 6.341, p = 0.016$*	$F(4, 40) = 0.415, p = 0.797$
Mandarin F5	50	$F(4, 40) = 1.984, p = 0.115$	$F(1, 40) = 21.448, p < 0.001$**	$F(4, 40) = 2.147, p = 0.093$
/a/				
Mandarin M1	70	$F(6, 56) = 1.797, p = 0.116$	$F(1, 56) = 2.694, p = 0.106$	$F(6, 56) = 1.872, p = 0.102$
Mandarin M2	68†	$F(6, 54) = 2.560, p = 0.030$*	$F(1, 54) = 0.072, p = 0.789$	$F(6, 54) = 1.104, p = 0.372$
Mandarin M3	69†	$F(6, 55) = 2.646, p = 0.025$*	$F(1, 55) = 8.108, p = 0.006$**	$F(6, 55) = 2.238, p = 0.053$
Mandarin M4	69†	$F(6, 55) = 1.722, p = 0.133$	$F(1, 55) = 2.518, p = 0.118$	$F(6, 55) = 1.397, p = 0.232$
Mandarin M5	70	$F(6, 56) = 1.182, p = 0.329$	$F(1, 56) = 0.220, p = 0.641$	$F(6, 56) = 0.361, p = 0.900$
Mandarin F1	69†	$F(6, 55) = 0.496, p = 0.809$	$F(1, 55) = 1.420, p = 0.238$	$F(6, 55) = 1.067, p = 0.394$
Mandarin F2	70	$F(6, 56) = 0.559, p = 0.761$	$F(1, 56) = 7.328, p = 0.009$**	$F(6, 56) = 0.791, p = 0.581$
Mandarin F3	70	$F(6, 56) = 0.660, p = 0.682$	$F(1, 56) = 3.928, p = 0.052$	$F(6, 56) = 0.577, p = 0.747$
Mandarin F4	70	$F(6, 56) = 2.897, p = 0.016$*	$F(1, 56) = 3.587, p = 0.063$	$F(6, 56) = 1.149, p = 0.347$
Mandarin F5	70	$F(6, 56) = 1.192, p = 0.324$	$F(1, 56) = 15.802, p < 0.001$*	$F(6, 56) = 1.423, p = 0.222$
/u/				
Mandarin M1	50	$F(4, 40) = 10.38, p < 0.001$**	$F(1, 40) = 0.983, p = 0.327$	$F(4, 40) = 2.758, p = 0.041$*
Mandarin M2	50	$F(4, 40) = 0.627, p = 0.646$	$F(1, 40) = 16.60, p < 0.001$**	$F(4, 40) = 1.927, p = 0.125$
Mandarin M3	50	$F(4, 40) = 0.369, p = 0.829$	$F(1, 40) = 0.410, p = 0.525$	$F(4, 40) = 0.619, p = 0.652$
Mandarin M4	50	$F(4, 40) = 0.993, p = 0.422$	$F(1, 40) = 0.008, p = 0.928$	$F(4, 40) = 0.116, p = 0.976$
Mandarin M5	50	$F(4, 40) = 1.687, p = 0.172$	$F(1, 40) = 8.208, p = 0.007$**	$F(4, 40) = 0.470, p = 0.757$
Mandarin F1	50	$F(4, 40) = 1.334, p = 0.274$	$F(1, 40) = 0.558, p = 0.460$	$F(4, 40) = 1.204, p = 0.324$
Mandarin F2	50	$F(4, 40) = 1.369, p = 0.262$	$F(1, 40) = 9.232, p = 0.004$**	$F(4, 40) = 1.524, p = 0.214$
Mandarin F3	50	$F(4, 40) = 0.646, p = 0.633$	$F(1, 40) = 1.229, p = 0.274$	$F(4, 40) = 1.990, p = 0.115$
Mandarin F4	50	$F(4, 40) = 0.975, p = 0.432$	$F(1, 40) = 0.391, p = 0.536$	$F(4, 40) = 0.433, p = 0.784$
Mandarin F5	50	$F(4, 40) = 1.839, p = 0.140$	$F(1, 40) = 9.745, p = 0.003$**	$F(4, 40) = 1.904, p = 0.129$

*Significant at 0.05 level
**Significant at 0.005 level
†Missing data

Appendix 16

Two-way (Tone by Task) ANOVA Results for Individual Mandarin Speakers – %jitter

Subject	N	Tone Effect	Task Effect	Tone x Task Interaction Effect
/i/				
Mandarin M1	40	$F(3, 32) = 19.483$, $p < 0.001$**	$F(1, 32) = 9.7440$, $p = 0.004$**	$F(3, 32) = 3.386$, $p = 0.030$*
Mandarin M2	40	$F(3, 32) = 17.615$, $p < 0.001$**	$F(1, 32) = 0.0028$, $p = 0.958$	$F(3, 32) = 0.327$, $p = 0.806$
Mandarin M3	40	$F(3, 32) = 97.767$, $p < 0.001$**	$F(1, 32) = 3.5360$, $p = 0.067$	$F(3, 32) = 1.136$, $p = 0.349$
Mandarin M4	40	$F(3, 32) = 9.3260$, $p < 0.001$**	$F(1, 32) = 0.0825$, $p = 0.776$	$F(3, 32) = 1.578$, $p = 0.214$
Mandarin M5	40	$F(3, 32) = 7.170$, $p < 0.001$**	$F(1, 32) = 10.050$, $p = 0.003$**	$F(3, 32) = 3.296$, $p = 0.033$*
Mandarin F1	40	$F(3, 32) = 34.99$, $p < 0.001$**	$F(1, 32) = 1.6350$, $p = 0.210$	$F(3, 32) = 1.428$, $p = 0.253$
Mandarin F2	40	$F(3, 32) = 20.19$, $p < 0.001$**	$F(1, 32) = 0.0147$, $p = 0.904$	$F(3, 32) = 0.651$, $p = 0.588$
Mandarin F3	40	$F(3, 32) = 3.002$, $p = 0.045$*	$F(1, 32) = 0.2120$, $p = 0.649$	$F(3, 32) = 2.555$, $p = 0.073$
Mandarin F4	40	$F(3, 32) = 2.126$, $p = 0.116$	$F(1, 32) = 0.8610$, $p = 0.360$	$F(3, 32) = 0.701$, $p = 0.559$
Mandarin F5	40	$F(3, 32) = 4.701$, $p = 0.008$**	$F(1, 32) = 9.8180$, $p = 0.004$**	$F(3, 32) = 2.814$, $p = 0.005$**
/a/				
Mandarin M1	40	$F(3, 32) = 18.52$, $p < 0.001$**	$F(1, 32) = 5.021$, $p = 0.032$*	$F(3, 32) = 4.221$, $p = 0.013$*
Mandarin M2	39†	$F(3, 31) = 6.416$, $p = 0.002$**	$F(1, 31) = 2.251$, $p = 0.144$	$F(3, 31) = 3.695$, $p = 0.022$*
Mandarin M3	40	$F(3, 32) = 10.57$, $p < 0.001$**	$F(1, 32) = 0.461$, $p = 0.502$	$F(3, 32) = 1.101$, $p = 0.363$
Mandarin M4	39†	$F(3, 31) = 5.891$, $p = 0.003$**	$F(1, 31) = 0.001$, $p = 0.970$	$F(3, 31) = 1.978$, $p = 0.138$
Mandarin M5	40	$F(3, 32) = 23.94$, $p < 0.001$**	$F(1, 32) = 0.119$, $p = 0.732$	$F(3, 32) = 1.620$, $p = 0.204$
Mandarin F1	40	$F(3, 32) = 3.478$, $p = 0.027$*	$F(1, 32) = 0.240$, $p = 0.628$	$F(3, 32) = 0.0197$, $p = 0.996$
Mandarin F2	40	$F(3, 32) = 13.58$, $p < 0.001$**	$F(1, 32) = 0.202$, $p = 0.656$	$F(3, 32) = 0.289$, $p = 0.833$
Mandarin F3	40	$F(3, 32) = 3.665$, $p = 0.022$*	$F(1, 32) = 0.0224$, $p = 0.882$	$F(3, 32) = 0.181$, $p = 0.909$
Mandarin F4	40	$F(3, 32) = 3.907$, $p = 0.017$*	$F(1, 32) = 0.157$, $p = 0.694$	$F(3, 32) = 0.0823$, $p = 0.969$
Mandarin F5	40	$F(3, 32) = 2.299$, $p = 0.096$	$F(1, 32) = 5.527$, $p = 0.025$*	$F(3, 32) = 2.222$, $p = 0.105$
/u/				
Mandarin M1	40	$F(3, 32) = 2.524$, $p = 0.075$	$F(1, 32) = 1.729$, $p = 0.198$	$F(3, 32) = 1.697$, $p = 0.187$
Mandarin M2	39†	$F(3, 31) = 16.45$, $p < 0.001$**	$F(1, 31) = 0.997$, $p = 0.326$	$F(3, 31) = 0.256$, $p = 0.857$
Mandarin M3	40	$F(3, 32) = 42.21$, $p < 0.001$**	$F(1, 32) = 2.649$, $p = 0.113$	$F(3, 32) = 1.012$, $p = 0.400$
Mandarin M4	40	$F(3, 32) = 17.10$, $p < 0.001$**	$F(1, 32) = 10.21$, $p = 0.003$**	$F(3, 32) =1.052$, $p = 0.383$
Mandarin M5	40	$F(3, 32) = 5.283$, $p = 0.004$**	$F(1, 32) = 5.610$, $p = 0.024$*	$F(3, 32) =1.358$, $p = 0.273$
Mandarin F1	40	$F(3, 32) = 5.338$, $p = 0.004$**	$F(1, 32) = 1.440$, $p = 0.239$	$F(3, 32) = 0.627$, $p = 0.603$
Mandarin F2	40	$F(3, 32) = 6.088$, $p = 0.002$**	$F(1, 32) = 0.869$, $p = 0.358$	$F(3, 32) = 0.867$, $p = 0.468$
Mandarin F3	40	$F(3, 32) = 2.020$, $p = 0.131$	$F(1, 32) = 2.941$, $p = 0.096$	$F(3, 32) = 1.078$, $p = 0.372$
Mandarin F4	40	$F(3, 32) = 3.251$, $p = 0.034$*	$F(1, 32) = 1.392$, $p = 0.247$	$F(3, 32) = 1.638$, $p = 0.200$
Mandarin F5	39†	$F(3, 31) = 3.457$, $p = 0.028$*	$F(1, 31) = 10.84$, $p = 0.002$**	$F(3, 31) = 2.2910$, $p = 0.098$

*Significant at 0.05 level
**Significant at 0.005 level
†Missing data

Appendix 17

Two-way (Consonant by Task) ANOVA Results for Individual English Speakers – %shimmer

Subject	N	Consonant Effect	Task Effect	Consonant x Task Interaction Effect
/i/				
English M1	40	F(3, 32) = 1.208, p = 0.323	F(1, 32) = 0.032, p = 0.859	F(3, 32) = 2.558, p = 0.072
English M2	40	F(3, 32) = 2.215, p = 0.105	F(1, 32) = 58.46, p < 0.001**	F(3, 32) = 1.579, p = 0.214
English M3	40	F(3, 32) = 1.606, p = 0.207	F(1, 32) = 11.67, p = 0.002**	F(3, 32) = 0.244, p = 0.865
English M4	40	F(3, 32) = 4.169, p = 0.013*	F(1, 32) = 1.562, p = 0.220	F(3, 32) = 0.338, p = 0.798
English M5	40	F(3, 32) = 1.780, p = 0.171	F(1, 32) = 3.619, p = 0.066	F(3, 32) = 2.473, p = 0.079
English F1	40	F(3, 32) = 3.562, p = 0.025*	F(1, 32) = 6.653, p = 0.015*	F(3, 32) = 2.836, p = 0.054
English F2	40	F(3, 32) = 0.400, p = 0.754	F(1, 32) = 2.589, p = 0.117	F(3, 32) = 0.701, p = 0.558
English F3	40	F(3, 32) = 0.816, p = 0.495	F(1, 32) = 0.113, p = 0.739	F(3, 32) = 0.992, p = 0.409
English F4	40	F(3, 32) = 0.347, p = 0.792	F(1, 32) = 0.0776, p = 0.782	F(3, 32) = 1.747, p = 0.177
English F5	40	F(3, 32) = 0.895, p = 0.454	F(1, 32) = 0.0539, p = 0.818	F(3, 32) = 0.0792, p = 0.971
/a/				
English M1	60	F(5, 48) = 1.852, p = 0.121	F(1, 48) = 8.5710, p = 0.005**	F(5, 48) = 1.654, p = 0.164
English M2	59†	F(5, 47) = 0.880, p = 0.502	F(1, 47) = 8.1730, p = 0.006**	F(5, 47) = 1.114, p = 0.366
English M3	60	F(5, 48) = 0.403, p = 0.844	F(1, 48) = 10.435, p = 0.002**	F(5, 48) = 0.716, p = 0.614
English M4	60	F(5, 48) = 0.841, p = 0.527	F(1, 48) = 0.8740, p = 0.354	F(5, 48) = 1.378, p = 0.249
English M5	60	F(5, 48) = 1.728, p = 0.146	F(1, 48) = 7.3150, p = 0.009**	F(5, 48) = 0.522, p = 0.759
English F1	60	F(5, 48) = 0.516, p = 0.763	F(1, 48) = 28.776, p < 0.001**	F(5, 48) = 2.072, p = 0.085
English F2	60	F(5, 48) = 1.066, p = 0.391	F(1, 48) = 0.1800, p = 0.673	F(5, 48) = 0.488, p = 0.783
English F3	59†	F(5, 47) = 2.085, p = 0.084	F(1, 47) = 35.844, p < 0.001**	F(5, 47) = 1.209, p = 0.320
English F4	60	F(5, 48) = 0.383, p = 0.858	F(1, 48) = 0.197, p = 0.659	F(5, 48) = 1.285, p = 0.286
English F5	60	F(5, 48) = 0.746, p = 0.593	F(1, 48) = 9.109, p = 0.004**	F(5, 48) = 1.627, p = 0.171
/u/				
English M1	40	F(3, 32) = 0.551, p = 0.651	F(1, 32) = 0.109, p = 0.744	F(3, 32) = 1.345, p = 0.277
English M2	40	F(3, 32) = 1.182, p = 0.332	F(1, 32) = 50.35, p < 0.001**	F(3, 32) = 1.957, p = 0.140
English M3	39†	F(3, 31) = 0.580, p = 0.632	F(1, 31) = 0.044, p = 0.835	F(3, 31) = 2.671, p = 0.065
English M4	40	F(3, 32) = 2.368, p = 0.089	F(1, 32) = 2.211, p = 0.147	F(3, 32) = 1.084, p = 0.370
English M5	38†	F(3, 30) = 9.893, p < 0.001**	F(1, 30) = 1.781, p = 0.192	F(3, 30) = 2.138, p = 0.116
English F1	40	F(3, 32) = 0.367, p = 0.777	F(1, 32) = 25.12, p < 0.001**	F(3, 32) = 0.0868, p = 0.967
English F2	40	F(3, 32) = 0.334, p = 0.801	F(1, 32) = 1.596, p = 0.216	F(3, 32) = 0.126, p = 0.944
English F3	40	F(3, 32) = 1.498, p = 0.234	F(1, 32) = 3.112, p = 0.087	F(3, 32) = 0.601, p = 0.619
English F4	40	F(3, 32) = 1.382, p = 0.266	F(1, 32) = 2.158, p = 0.152	F(3, 32) = 2.429, p = 0.083
English F5	38†	F(3, 30) = 0.746, p = 0.533	F(1, 30) = 4.208, p = 0.049*	F(3, 30) = 0.865, p = 0.470

*Significant at 0.05 level
**Significant at 0.005 level
†Missing data

Appendix 18

Two-way (Consonant by Task) ANOVA Results for Individual Mandarin Speakers – %shimmer

Subject	N	Consonant Effect	Task Effect	Consonant x Task Interaction Effect
/i/				
Mandarin M1	50	F(4, 40) = 1.106, p = 0.367	F(1, 40) = 1.081, p = 0.305	F(4, 40) = 1.145, p = 0.349
Mandarin M2	49[†]	F(4, 39) = 4.031, p = 0.008**	F(1, 39) = 42.987, p < 0.001**	F(4, 39) = 0.965, p = 0.438
Mandarin M3	50	F(4, 40) = 3.317, p = 0.019*	F(1, 40) = 4.125, p = 0.049*	F(4, 40) = 0.071, p = 0.991
Mandarin M4	50	F(4, 40) = 0.541, p = 0.707	F(1, 40) = 1.148, p = 0.290	F(4, 40) = 1.237, p = 0.311
Mandarin M5	50	F(4, 40) = 0.158, p = 0.958	F(1, 40) = 22.949, p < 0.001**	F(4, 40) = 1.212, p = 0.321
Mandarin F1	50	F(4, 40) = 3.909, p = 0.009**	F(1, 40) = 23.622, p < 0.001**	F(4, 40) = 0.613, p = 0.656
Mandarin F2	49[†]	F(4, 39) = 1.520, p = 0.215	F(1, 39) = 0.455, p = 0.504	F(4, 39) = 0.571, p = 0.685
Mandarin F3	49[†]	F(4, 39) = 0.481, p = 0.749	F(1, 39) = 6.363, p = 0.016*	F(4, 39) = 0.311, p = 0.869
Mandarin F4	50	F(4, 40) = 1.495, p = 0.222	F(1, 40) = 18.055, p < 0.001**	F(4, 40) = 0.263, p = 0.900
Mandarin F5	50	F(4, 40) = 0.183, p = 0.946	F(1, 40) = 30.601, p < 0.001**	F(4, 40) = 1.822, p = 0.144
/a/				
Mandarin M1	70	F(6, 56) = 1.745, p = 0.128	F(1, 56) = 0.144, p = 0.705	F(6, 56) = 0.991, p = 0.441
Mandarin M2	68[†]	F(6, 54) = 4.073, p = 0.002**	F(1, 54) = 29.579, p < 0.001**	F(6, 54) = 2.041, p = 0.076
Mandarin M3	69[†]	F(6, 55) = 1.917, p = 0.094	F(1, 55) = 1.114, p = 0.296	F(6, 55) = 0.220, p = 0.969
Mandarin M4	69[†]	F(6, 55) = 1.448, p = 0.213	F(1, 55) = 0.192, p = 0.663	F(6, 55) = 1.316, p = 0.265
Mandarin M5	70	F(6, 56) = 3.815, p = 0.003**	F(1, 56) = 0.414, p = 0.523	F(6, 56) = 0.980, p = 0.447
Mandarin F1✧	69[†]	F(6, 55) = 1.094, p = 0.378	F(1, 55) = 6.392, p = 0.014*	F(6, 55) = 1.933, p = 0.092
Mandarin F2	70	F(6, 56) = 0.887, p = 0.511	F(1, 56) = 4.207, p = 0.045*	F(6, 56) = 2.217, p = 0.055
Mandarin F3	70	F(6, 56) = 0.813, p = 0.564	F(1, 56) = 0.555, p = 0.459	F(6, 56) = 0.631, p = 0.705
Mandarin F4	70	F(6, 56) = 2.374, p = 0.041*	F(1, 56) = 8.807, p = 0.004**	F(6, 56) = 0.920, p = 0.488
Mandarin F5	70	F(6, 56) = 0.498, p = 0.807	F(1, 56) = 30.607, p < 0.001**	F(6, 56) = 0.643, p = 0.695
/u/				
Mandarin M1	50	F(4, 40) = 0.337, p = 0.852	F(1, 40) = 8.911, p = 0.005**	F(4, 40) = 0.235, p = 0.917
Mandarin M2	50	F(4, 40) = 1.428, p = 0.243	F(1, 40) = 6.790, p = 0.013*	F(4, 40) = 0.400, p = 0.807
Mandarin M3	50	F(4, 40) = 1.310, p = 0.283	F(1, 40) = 4.404, p = 0.042*	F(4, 40) = 0.417, p = 0.795
Mandarin M4	50	F(4, 40) = 1.202, p = 0.325	F(1, 40) = 0.0797, p = 0.779	F(4, 40) = 2.027, p = 0.109
Mandarin M5	50	F(4, 40) = 0.237, p = 0.916	F(1, 40) = 1.865, p = 0.180	F(4, 40) = 0.814, p = 0.524
Mandarin F1	50	F(4, 40) = 1.265, p = 0.300	F(1, 40) = 1.434, p = 0.238	F(4, 40) = 0.463, p = 0.762
Mandarin F2	50	F(4, 40) = 1.340, p = 0.272	F(1, 40) = 1.479, p = 0.231	F(4, 40) = 2.306, p = 0.075
Mandarin F3	50	F(4, 40) = 0.440, p = 0.779	F(1, 40) = 4.308, p = 0.044*	F(4, 40) = 1.755, p = 0.157
Mandarin F4	50	F(4, 40) = 0.898, p = 0.474	F(1, 40) = 4.514, p = 0.040*	F(4, 40) = 1.011, p = 0.413
Mandarin F5	50	F(4, 40) = 1.661, p = 0.178	F(1, 40) = 19.694, p < 0.001**	F(4, 40) = 1.760, p = 0.156

*Significant at 0.05 level
**Significant at 0.005 level
[†]Missing data

Appendix 19

Two-way (Tone by Task) ANOVA Results for Individual Mandarin Speakers – %shimmer

Subject	N	Tone Effect	Task Effect	Tone x Task Interaction Effect
/i/				
Mandarin M1	40	$F(3, 32) = 15.690, p < 0.001$**	$F(1, 32) = 8.5570, p = 0.006$**	$F(3, 32) = 2.532, p = 0.075$
Mandarin M2	40	$F(3, 32) = 3.8010, p = 0.019$*	$F(1, 32) = 8.1510, p = 0.007$**	$F(3, 32) = 0.770, p = 0.519$
Mandarin M3	40	$F(3, 32) = 31.464, p < 0.001$**	$F(1, 32) = 0.6180, p = 0.438$	$F(3, 32) = 0.545, p = 0.655$
Mandarin M4	40	$F(3, 32) = 6.9120, p = 0.001$**	$F(1, 32) = 1.7000, p = 0.202$	$F(3, 32) = 4.376, p = 0.011$*
Mandarin M5	40	$F(3, 32) = 11.810, p < 0.001$**	$F(1, 32) = 23.218, p < 0.001$**	$F(3, 32) = 3.062, p = 0.042$*
Mandarin F1	40	$F(3, 32) = 18.442, p < 0.001$**	$F(1, 32) = 0.1940, p = 0.662$	$F(3, 32) = 6.950, p < 0.001$**
Mandarin F2	40	$F(3, 32) = 29.296, p < 0.001$**	$F(1, 32) = 0.5650, p = 0.458$	$F(3, 32) = 0.386, p = 0.764$
Mandarin F3	40	$F(3, 32) = 1.353, p = 0.275$	$F(1, 32) = 1.3290, p = 0.258$	$F(3, 32) = 1.246, p = 0.309$
Mandarin F4	40	$F(3, 32) = 3.773, p = 0.020$*	$F(1, 32) = 0.0269, p = 0.871$	$F(3, 32) = 0.493, p = 0.689$
Mandarin F5	40	$F(3, 32) = 7.358, p < 0.001$**	$F(1, 32) = 11.836, p = 0.002$**	$F(3, 32) = 4.839, p = 0.007$**
/a/				
Mandarin M1	40	$F(3, 32) = 2.888, p = 0.051$	$F(1, 32) = 0.881, p = 0.355$	$F(3, 32) = 1.003, p = 0.404$
Mandarin M2	39†	$F(3, 31) = 1.485, p = 0.238$	$F(1, 31) = 0.111, p = 0.741$	$F(3, 31) = 2.822, p = 0.055$
Mandarin M3	40	$F(3, 32) = 9.218, p < 0.001$**	$F(1, 32) = 0.107, p = 0.746$	$F(3, 32) = 2.725, p = 0.060$
Mandarin M4	39†	$F(3, 31) = 3.202, p = 0.037$*	$F(1, 31) = 1.276, p = 0.267$	$F(3, 31) = 0.165, p = 0.919$
Mandarin M5	40	$F(3, 32) = 15.76, p < 0.001$**	$F(1, 32) = 0.00001, p = 0.997$	$F(3, 32) = 0.659, p = 0.583$
Mandarin F1	40	$F(3, 32) = 12.75, p < 0.001$**	$F(1, 32) = 0.0001, p = 0.991$	$F(3, 32) = 3.632, p = 0.023$*
Mandarin F2	40	$F(3, 32) = 13.93, p < 0.001$**	$F(1, 32) = 0.311, p = 0.581$	$F(3, 32) = 0.195, p = 0.899$
Mandarin F3	40	$F(3, 32) = 2.525, p = 0.075$	$F(1, 32) = 0.523, p = 0.475$	$F(3, 32) = 0.393, p = 0.759$
Mandarin F4	40	$F(3, 32) = 3.039, p = 0.043$*	$F(1, 32) = 0.0810, p = 0.778$	$F(3, 32) = 0.177, p = 0.911$
Mandarin F5	40	$F(3, 32) = 5.419, p = 0.004$**	$F(1, 32) = 16.393, p < 0.001$**	$F(3, 32) = 3.624, p = 0.023$*
/u/				
Mandarin M1	40	$F(3, 32) = 3.675, p = 0.022$*	$F(1, 32) = 0.760, p = 0.390$	$F(3, 32) = 1.019, p = 0.397$
Mandarin M2	39†	$F(3, 31) = 3.454, p = 0.028$*	$F(1, 31) = 0.608, p = 0.441$	$F(3, 31) = 0.726, p = 0.544$
Mandarin M3	40	$F(3, 32) = 7.118, p < 0.001$**	$F(1, 32) = 0.376, p = 0.544$	$F(3, 32) = 1.563, p = 0.217$
Mandarin M4	40	$F(3, 32) = 1.203, p = 0.324$	$F(1, 32) = 4.389, p = 0.044$*	$F(3, 32) = 0.328, p = 0.805$
Mandarin M5	40	$F(3, 32) = 11.05, p < 0.001$**	$F(1, 32) = 7.614, p = 0.010$*	$F(3, 32) = 1.616, p = 0.205$
Mandarin F1	40	$F(3, 32) = 4.796, p = 0.007$**	$F(1, 32) = 1.287, p = 0.265$	$F(3, 32) = 0.607, p = 0.615$
Mandarin F2	40	$F(3, 32) = 6.280, p = 0.002$**	$F(1, 32) = 2.590, p = 0.117$	$F(3, 32) = 1.894, p = 0.150$
Mandarin F3	40	$F(3, 32) = 1.594, p = 0.210$	$F(1, 32) = 4.197, p = 0.049$*	$F(3, 32) = 1.542, p = 0.223$
Mandarin F4	40	$F(3, 32) = 4.421, p = 0.010$*	$F(1, 32) = 1.643, p = 0.209$	$F(3, 32) = 1.348, p = 0.276$
Mandarin F5	39†	$F(3, 31) =2.564, p = 0.073$	$F(1, 31) = 10.91, p = 0.002$**	$F(3, 31) = 1.912, p = 0.148$

*Significant at 0.05 level
**Significant at 0.005 level
†Missing data

Appendix 20

Two-way (Consonant by Task) ANOVA Results for Individual English Speakers – SNR

Subject	N	Consonant Effect	Task Effect	Consonant x Task Interaction Effect
/i/				
English M1	40	$F(3, 32) = 1.093$, $p = 0.366$	$F(1, 32) = 0.0634$, $p = 0.803$	$F(3, 32) = 3.645$, $p = 0.023$*
English M2	40	$F(3, 32) = 4.320$, $p = 0.011$*	$F(1, 32) = 2.802$, $p = 0.104$	$F(3, 32) = 0.320$, $p = 0.811$
English M3	40	$F(3, 32) = 0.836$, $p = 0.484$	$F(1, 32) = 2.216$, $p = 0.146$	$F(3, 32) = 0.807$, $p = 0.499$
English M4	40	$F(3, 32) = 0.276$, $p = 0.842$	$F(1, 32) = 0.227$, $p = 0.637$	$F(3, 32) = 2.118$, $p = 0.117$
English M5	40	$F(3, 32) = 4.371$, $p = 0.011$*	$F(1, 32) = 31.64$, $p < 0.001$**	$F(3, 32) = 1.186$, $p = 0.331$
English F1	40	$F(3, 32) = 4.066$, $p = 0.015$*	$F(1, 32) = 1.846$, $p = 0.184$	$F(3, 32) = 3.491$, $p = 0.027$*
English F2	40	$F(3, 32) = 2.639$, $p = 0.066$	$F(1, 32) = 1.376$, $p = 0.250$	$F(3, 32) = 0.624$, $p = 0.605$
English F3	40	$F(3, 32) = 0.583$, $p = 0.631$	$F(1, 32) = 1.723$, $p = 0.199$	$F(3, 32) = 2.029$, $p = 0.130$
English F4	40	$F(3, 32) = 2.840$, $p = 0.053$	$F(1, 32) = 1.604$, $p = 0.214$	$F(3, 32) = 2.182$, $p = 0.109$
English F5	40	$F(3, 32) = 0.562$, $p = 0.644$	$F(1, 32) = 1.682$, $p = 0.204$	$F(3, 32) = 0.205$, $p = 0.892$
/a/				
English M1	60	$F(5, 48) = 2.895$, $p = 0.023$*	$F(1, 48) = 9.6940$, $p = 0.003$**	$F(5, 48) = 3.400$, $p = 0.010$*
English M2	59†	$F(5, 47) = 1.022$, $p = 0.416$	$F(1, 47) = 4.5330$, $p = 0.039$*	$F(5, 47) = 0.721$, $p = 0.611$
English M3	60	$F(5, 48) = 0.738$, $p = 0.598$	$F(1, 48) = 16.956$, $p < 0.001$**	$F(5, 48) = 0.608$, $p = 0.694$
English M4	60	$F(5, 48) = 0.384$, $p = 0.857$	$F(1, 48) = 0.5320$, $p = 0.469$	$F(5, 48) = 1.241$, $p = 0.305$
English M5	60	$F(5, 48) = 0.742$, $p = 0.596$	$F(1, 48) = 6.4730$, $p = 0.014$*	$F(5, 48) = 1.126$, $p = 0.359$
English F1	60	$F(5, 48) = 0.678$, $p = 0.642$	$F(1, 48) = 9.7860$, $p = 0.003$**	$F(5, 48) = 1.343$, $p = 0.263$
English F2	60	$F(5, 48) = 0.947$, $p = 0.460$	$F(1, 48) = 0.0467$, $p = 0.830$	$F(5, 48) = 0.616$, $p = 0.688$
English F3	59†	$F(5, 47) = 1.034$, $p = 0.409$	$F(1, 47) = 12.731$, $p < 0.001$**	$F(5, 47) = 0.068$, $p = 0.997$
English F4	60	$F(5, 48) = 0.141$, $p = 0.982$	$F(1, 48) = 0.1010$, $p = 0.752$	$F(5, 48) = 0.472$, $p = 0.795$
English F5	60	$F(5, 48) = 0.229$, $p = 0.948$	$F(1, 48) = 22.347$, $p < 0.001$**	$F(5, 48) = 2.589$, $p = 0.038$*
/u/				
English M1	40	$F(3, 32) = 0.598$, $p = 0.621$	$F(1, 32) = 1.9360$, $p = 0.174$	$F(3, 32) = 1.711$, $p = 0.184$
English M2	40	$F(3, 32) = 5.407$, $p = 0.004$**	$F(1, 32) = 82.637$, $p < 0.001$**	$F(3, 32) = 0.445$, $p = 0.722$
English M3	39†	$F(3, 31) = 6.267$, $p = 0.002$**	$F(1, 31) = 11.279$, $p = 0.002$**	$F(3, 31) = 0.075$, $p = 0.973$
English M4	40	$F(3, 32) = 0.135$, $p = 0.939$	$F(1, 32) = 12.785$, $p = 0.001$**	$F(3, 32) = 0.084$, $p = 0.968$
English M5	38†	$F(3, 30) = 1.310$, $p = 0.289$	$F(1, 30) = 6.575$, $p = 0.016$*	$F(3, 30) = 0.469$, $p = 0.706$
English F1	40	$F(3, 32) = 1.857$, $p = 0.157$	$F(1, 32) = 0.902$, $p = 0.349$	$F(3, 32) = 0.026$, $p = 0.994$
English F2	40	$F(3, 32) = 0.719$, $p = 0.548$	$F(1, 32) = 2.382$, $p = 0.133$	$F(3, 32) = 1.964$, $p = 0.139$
English F3	40	$F(3, 32) = 3.022$, $p = 0.044$*	$F(1, 32) = 5.962$, $p = 0.020$*	$F(3, 32) = 1.733$, $p = 0.180$
English F4	40	$F(3, 32) = 1.201$, $p = 0.325$	$F(1, 32) = 17.346$, $p < 0.001$**	$F(3, 32) = 3.599$, $p = 0.024$*
English F5	38†	$F(3, 30) = 2.755$, $p = 0.060$	$F(1, 30) = 8.6620$, $p = 0.006$**	$F(3, 30) = 1.386$, $p = 0.266$

*Significant at 0.05 level
**Significant at 0.005 level
†Missing data

Appendix 21

Two-way (Consonant by Task) ANOVA Results for Individual Mandarin Speakers – SNR

Subject	N	Consonant Effect	Task Effect	Consonant x Task Interaction Effect
/i/				
Mandarin M1	50	F(4, 40) = 0.472, p = 0.756	F(1, 40) = 0.156, p = 0.695	F(4, 40) = 1.879, p = 0.133
Mandarin M2	49†	F(4, 39) = 0.465, p = 0.761	F(1, 39) = 4.896, p = 0.033*	F(4, 39) = 2.330, p = 0.073
Mandarin M3	50	F(4, 40) = 1.296, p = 0.288	F(1, 40) = 0.694, p = 0.410	F(4, 40) = 0.493, p = 0.741
Mandarin M4	50	F(4, 40) = 0.686, p = 0.606	F(1, 40) = 0.033, p = 0.857	F(4, 40) = 0.975, p = 0.432
Mandarin M5	50	F(4, 40) = 1.411, p = 0.248	F(1, 40) = 31.30, p < 0.001**	F(4, 40) = 2.013, p = 0.111
Mandarin F1	50	F(4, 40) = 1.062, p = 0.388	F(1, 40) = 9.331, p = 0.004**	F(4, 40) = 0.599, p = 0.665
Mandarin F2	49†	F(4, 39) = 0.253, p = 0.906	F(1, 39) = 0.664, p = 0.420	F(4, 39) = 0.936, p = 0.453
Mandarin F3	49†	F(4, 39) = 0.371, p = 0.828	F(1, 39) = 3.631, p = 0.064	F(4, 39) = 0.443, p = 0.777
Mandarin F4	50	F(4, 40) = 1.029, p = 0.404	F(1, 40) = 31.97, p < 0.001**	F(4, 40) = 0.360, p = 0.836
Mandarin F5	50	F(4, 40) = 1.579, p = 0.199	F(1, 40) = 14.55, p < 0.001**	F(4, 40) = 0.812, p = 0.525
/a/				
Mandarin M1	70	F(6, 56) = 0.756, p = 0.607	F(1, 56) = 11.503, p = 0.001**	F(6, 56) = 0.492, p = 0.811
Mandarin M2	68†	F(6, 54) = 1.899, p = 0.098	F(1, 54) = 0.339, p = 0.563	F(6, 54) = 1.665, p = 0.147
Mandarin M3	69†	F(6, 55) = 3.453, p = 0.006**	F(1, 55) = 3.961, p = 0.052	F(6, 55) = 0.957, p = 0.463
Mandarin M4	69†	F(6, 55) = 1.024, p = 0.420	F(1, 55) = 0.838, p = 0.364	F(6, 55) = 1.708, p = 0.137
Mandarin M5	70	F(6, 56) = 0.527, p = 0.786	F(1, 56) = 48.52, p < 0.001**	F(6, 56) = 0.632, p = 0.704
Mandarin F1	69†	F(6, 55) = 0.300, p = 0.934	F(1, 55) = 0.080, p = 0.779	F(6, 55) = 0.925, p = 0.484
Mandarin F2	70	F(6, 56) = 0.791, p = 0.581	F(1, 56) = 2.175, p = 0.146	F(6, 56) = 0.773, p = 0.595
Mandarin F3	70	F(6, 56) = 0.787, p = 0.583	F(1, 56) = 17.25, p < 0.001**	F(6, 56) = 0.678, p = 0.668
Mandarin F4	70	F(6, 56) = 2.394, p = 0.040*	F(1, 56) = 1.499, p = 0.226	F(6, 56) = 0.810, p = 0.567
Mandarin F5	70	F(6, 56) = 0.969, p = 0.455	F(1, 56) = 13.54, p < 0.001**	F(6, 56) = 0.591, p = 0.736
/u/				
Mandarin M1	50	F(4, 40) = 1.719, p = 0.165	F(1, 40) = 0.7270, p = 0.399	F(4, 40) = 0.950, p = 0.445
Mandarin M2	50	F(4, 40) = 0.539, p = 0.708	F(1, 40) = 0.0362, p = 0.850	F(4, 40) = 0.462, p = 0.763
Mandarin M3	50	F(4, 40) = 3.536, p = 0.015*	F(1, 40) = 0.9770, p = 0.329	F(4, 40) = 1.416, p = 0.246
Mandarin M4	50	F(4, 40) = 2.039, p = 0.107	F(1, 40) = 1.9230, p = 0.173	F(4, 40) = 1.502, p = 0.220
Mandarin M5	50	F(4, 40) = 2.588, p = 0.051	F(1, 40) = 0.0484, p = 0.827	F(4, 40) = 0.869, p = 0.491
Mandarin F1	50	F(4, 40) = 3.467, p = 0.016*	F(1, 40) = 0.2670, p = 0.608	F(4, 40) = 1.342, p = 0.271
Mandarin F2	50	F(4, 40) = 1.511, p = 0.217	F(1, 40) = 19.996, p < 0.001**	F(4, 40) = 1.320, p = 0.279
Mandarin F3	50	F(4, 40) = 0.711, p = 0.589	F(1, 40) = 0.1280, p = 0.722	F(4, 40) = 1.552, p = 0.206
Mandarin F4	50	F(4, 40) = 1.833, p = 0.141	F(1, 40) = 8.3660, p = 0.006**	F(4, 40) = 0.651, p = 0.630
Mandarin F5	50	F(4, 40) = 0.647, p = 0.632	F(1, 40) = 20.501, p < 0.001**	F(4, 40) = 1.354, p = 0.267

*Significant at 0.05 level
**Significant at 0.005 level
†Missing data

Appendix 22

Two-way (Tone by Task) ANOVA Results for Individual Mandarin Speakers – SNR

Subject	N	Tone Effect	Task Effect	Tone x Task Interaction Effect
/i/				
Mandarin M1	40	$F(3, 32) = 15.464, p < 0.001$**	$F(1, 32) = 0.005, p = 0.944$	$F(3, 32) = 0.971, p = 0.418$
Mandarin M2	40	$F(3, 32) = 6.8730, p = 0.001$**	$F(1, 32) = 4.456, p = 0.043$*	$F(3, 32) = 0.824, p = 0.490$
Mandarin M3	40	$F(3, 32) = 66.807, p < 0.001$**	$F(1, 32) = 1.002, p = 0.324$	$F(3, 32) = 1.650, p = 0.197$
Mandarin M4	40	$F(3, 32) = 11.533, p < 0.001$**	$F(1, 32) = 0.001, p = 0.974$	$F(3, 32) = 1.984, p = 0.136$
Mandarin M5	40	$F(3, 32) = 15.469, p < 0.001$**	$F(1, 32) = 17.55, p < 0.001$**	$F(3, 32) = 3.164, p = 0.038$*
Mandarin F1	40	$F(3, 32) = 2.6170, p = 0.068$	$F(1, 32) = 1.438, p = 0.239$	$F(3, 32) = 2.647, p = 0.066$
Mandarin F2	40	$F(3, 32) = 13.549, p < 0.001$**	$F(1, 32) = 1.072, p = 0.308$	$F(3, 32) = 0.449, p = 0.720$
Mandarin F3	40	$F(3, 32) = 1.3720, p = 0.269$	$F(1, 32) = 0.909, p = 0.348$	$F(3, 32) = 2.508, p = 0.076$
Mandarin F4	40	$F(3, 32) = 8.1720, p < 0.001$**	$F(1, 32) = 0.011, p = 0.919$	$F(3, 32) = 1.389, p = 0.264$
Mandarin F5	40	$F(3, 32) = 3.7980, p = 0.019$*	$F(1, 32) = 7.553, p = 0.010$*	$F(3, 32) = 4.078, p = 0.015$*
/a/				
Mandarin M1	40	$F(3, 32) = 27.083, p < 0.001$**	$F(1, 32) = 10.11, p = 0.003$**	$F(3, 32) = 1.456, p = 0.245$
Mandarin M2	39†	$F(3, 31) = 18.107, p < 0.001$**	$F(1, 31) = 4.757, p = 0.037$*	$F(3, 31) = 2.917, p = 0.050$
Mandarin M3	40	$F(3, 32) = 34.143, p < 0.001$**	$F(1, 32) = 0.005, p = 0.944$	$F(3, 32) = 2.385, p = 0.088$
Mandarin M4	39†	$F(3, 31) = 17.508, p < 0.001$**	$F(1, 31) = 0.453, p = 0.506$	$F(3, 31) = 1.402, p = 0.261$
Mandarin M5	40	$F(3, 32) = 41.063, p < 0.001$**	$F(1, 32) = 5.882, p = 0.021$*	$F(3, 32) = 0.896, p = 0.454$
Mandarin F1	40	$F(3, 32) = 5.2850, p = 0.004$**	$F(1, 32) = 0.209, p = 0.651$	$F(3, 32) = 0.851, p = 0.476$
Mandarin F2	40	$F(3, 32) = 26.562, p < 0.001$**	$F(1, 32) = 1.561, p = 0.221$	$F(3, 32) = 0.602, p = 0.618$
Mandarin F3	40	$F(3, 32) = 10.257, p < 0.001$**	$F(1, 32) = 4.473, p = 0.042$*	$F(3, 32) = 0.335, p = 0.800$
Mandarin F4	40	$F(3, 32) = 6.712, p = 0.001$**	$F(1, 32) = 1.340, p = 0.256$	$F(3, 32) = 0.378, p = 0.770$
Mandarin F5	40	$F(3, 32) = 5.574, p = 0.003$**	$F(1, 32) = 2.164, p = 0.151$	$F(3, 32) = 3.076, p = 0.041$*
/u/				
Mandarin M1	40	$F(3, 32) = 6.808, p = 0.001$**	$F(1, 32) = 0.727, p = 0.400$	$F(3, 32) = 0.450, p = 0.719$
Mandarin M2	39†	$F(3, 31) = 11.21, p < 0.001$**	$F(1, 31) = 0.027, p = 0.870$	$F(3, 31) = 0.835, p = 0.485$
Mandarin M3	40	$F(3, 32) = 25.51, p < 0.001$**	$F(1, 32) = 2.410, p = 0.130$	$F(3, 32) = 1.628, p = 0.202$
Mandarin M4	40	$F(3, 32) = 8.669, p < 0.001$**	$F(1, 32) = 4.925, p = 0.034$*	$F(3, 32) = 0.732, p = 0.540$
Mandarin M5	40	$F(3, 32) = 9.388, p < 0.001$**	$F(1, 32) = 5.253, p = 0.029$*	$F(3, 32) = 1.019, p = 0.397$
Mandarin F1	40	$F(3, 32) = 3.918, p = 0.017$*	$F(1, 32) = 0.0004, p = 0.983$	$F(3, 32) = 0.595, p = 0.623$
Mandarin F2	40	$F(3, 32) = 13.12, p < 0.001$**	$F(1, 32) = 0.197, p = 0.660$	$F(3, 32) = 0.375, p = 0.772$
Mandarin F3	40	$F(3, 32) = 1.711, p = 0.185$	$F(1, 32) = 1.444, p = 0.238$	$F(3, 32) = 1.399, p = 0.261$
Mandarin F4	40	$F(3, 32) = 5.013, p = 0.006$**	$F(1, 32) = 1.693, p = 0.202$	$F(3, 32) = 0.829, p = 0.488$
Mandarin F5	39†	$F(3, 31) = 3.151, p = 0.039$*	$F(1, 31) = 46.206, p < 0.001$**	$F(3, 31) = 1.359, p = 0.273$

*Significant at 0.05 level
**Significant at 0.005 level
†Missing data

Appendix 23

Two-way (Consonant by Task) ANOVA Results for Individual English Speakers – SQ90

Subject	N	Consonant Effect	Task Effect	Consonant x Task Interaction Effect
/i/				
English M1	31†	$F(3, 23) = 2.448$, $p = 0.089$	$F(1, 23) = 1.509$, $p = 0.232$	$F(3, 23) = 1.298$, $p = 0.299$
English M2	16†	$F(3, 11) = 0.628$, $p = 0.612$	$F(1, 11) = 2.974$, $p = 0.113$	--
English M3	37†	$F(3, 29) = 4.740$, $p = 0.008$**	$F(1, 29) = 40.95$, $p < 0.001$**	$F(3, 29) = 0.734$, $p = 0.540$
English M4	40	$F(3, 32) = 1.336$, $p = 0.280$	$F(1, 32) = 3.015$, $p = 0.092$	$F(3, 32) = 2.528$, $p = 0.075$
English M5	31†	$F(3, 23) = 2.677$, $p = 0.071$	$F(1, 23) = 8.918$, $p = 0.007$**	$F(3, 23) = 4.250$, $p = 0.016$*
English F1	12†	$F(3, 7) = 0.8930$, $p = 0.490$	$F(1, 7) = 2.6470$, $p = 0.148$	--
English F2	37†	$F(3, 29) = 1.307$, $p = 0.291$	$F(1, 29) = 0.246$, $p = 0.624$	$F(3, 29) = 1.421$, $p = 0.257$
English F3	40	$F(3, 32) = 0.866$, $p = 0.469$	$F(1, 32) = 2.033$, $p = 0.164$	$F(3, 32) = 1.830$, $p = 0.161$
English F4	28†	$F(3, 20) = 5.719$, $p = 0.005$**	$F(1, 20) = 1.722$, $p = 0.204$	$F(3, 20) = 2.757$, $p = 0.069$
English F5	34†	$F(3, 26) = 3.378$, $p = 0.033$*	$F(1, 26) = 0.032$, $p = 0.859$	$F(3, 26) = 1.297$, $p = 0.297$
/a/				
English M1	42†	$F(5, 30) = 1.184$, $p = 0.340$	$F(1, 30) = 1.212$, $p = 0.280$	$F(5, 30) = 1.169$, $p = 0.347$
English M2	30†	$F(5, 23) = 1.348$, $p = 0.280$	$F(1, 23) = 0.131$, $p = 0.720$	--
English M3	57†	$F(5, 45) = 3.608$, $p = 0.008$**	$F(1, 45) = 1.753$, $p = 0.192$	$F(5, 45) = 1.194$, $p = 0.328$
English M4	59†	$F(5, 47) = 1.716$, $p = 0.149$	$F(1, 47) = 0.207$, $p = 0.651$	$F(5, 47) = 1.167$, $p = 0.339$
English M5	49†	$F(5, 37) = 1.073$, $p = 0.391$	$F(1, 37) = 35.551$, $p < 0.001$**	$F(5, 37) = 0.590$, $p = 0.708$
English F1	20†	--	--	--
English F2	59†	$F(5, 47) = 0.400$, $p = 0.847$	$F(1, 47) = 0.396$, $p = 0.532$	$F(5, 47) = 0.448$, $p = 0.812$
English F3	59†	$F(5, 47) = 2.790$, $p = 0.028$*	$F(1, 47) = 7.286$, $p = 0.010$*	$F(5, 47) = 1.927$, $p = 0.108$
English F4	54†	$F(5, 42) = 2.416$, $p = 0.052$	$F(1, 42) = 0.049$, $p = 0.826$	$F(5, 42) = 1.274$, $p = 0.293$
English F5	46†	$F(5, 34) = 0.759$, $p = 0.585$	$F(1, 34) = 1.803$, $p = 0.188$	$F(5, 34) = 0.898$, $p = 0.493$
/u/				
English M1	39†	$F(3, 31) = 0.350$, $p = 0.789$	$F(1, 31) = 3.884$, $p = 0.058$	$F(3, 31) = 0.321$, $p = 0.810$
English M2	19†	$F(3, 14) = 1.941$, $p = 0.169$	$F(1, 14) = 6.215$, $p = 0.026$*	--
English M3	36†	$F(3, 28) = 6.492$, $p = 0.002$**	$F(1, 28) = 0.022$, $p = 0.883$	$F(3, 28) = 10.32$, $p < 0.001$**
English M4	40	$F(3, 32) = 2.574$, $p = 0.071$	$F(1, 32) = 3.309$, $p = 0.078$	$F(3, 32) = 1.377$, $p = 0.267$
English M5	27†	$F(3, 19) = 1.268$, $p = 0.314$	$F(1, 19) = 1.744$, $p = 0.202$	$F(3, 19) = 3.087$, $p = 0.052$
English F1	18†	$F(3, 13) = 0.436$, $p = 0.731$	$F(1, 13) = 5.517$, $p = 0.035$*	--
English F2	23†	$F(3, 15) = 1.358$, $p = 0.293$	$F(1, 15) = 7.310$, $p = 0.016$*	$F(3, 15) = 0.898$, $p = 0.465$
English F3	39†	$F(3, 31) = 0.188$, $p = 0.904$	$F(1, 31) = 29.25$, $p < 0.001$**	$F(3, 31) = 1.294$, $p = 0.294$
English F4	28†	$F(3, 20) = 0.605$, $p = 0.619$	$F(1, 20) = 3.324$, $p = 0.083$	$F(3, 20) = 1.092$, $p = 0.375$
English F5	27†	$F(3, 19) = 0.899$, $p = 0.460$	$F(1, 19) = 0.020$, $p = 0.888$	$F(3, 19) = 1.697$, $p = 0.201$

*Significant at 0.05 level
**Significant at 0.005 level
†Missing data

Appendix 24

Two-way (Consonant by Task) ANOVA Results for Individual Mandarin Speakers – SQ90

Subject	N	Consonant Effect	Task Effect	Consonant x Task Interaction Effect
/i/				
Mandarin M1	28†	$F(4, 22) = 0.817, p = 0.528$	$F(1, 22) = 0.632, p = 0.435$	--
Mandarin M2	43†	$F(4, 33) = 0.391, p = 0.814$	$F(1, 33) = 0.224, p = 0.639$	$F(4, 33) = 0.521, p = 0.721$
Mandarin M3	49†	$F(4, 39) = 1.379, p = 0.259$	$F(1, 39) = 0.085, p = 0.772$	$F(4, 39) = 2.130, p = 0.095$
Mandarin M4	50	$F(4, 40) = 1.007, p = 0.415$	$F(1, 40) = 3.697, p = 0.062$	$F(4, 40) = 1.927, p = 0.125$
Mandarin M5	49†	$F(4, 39) = 2.095, p = 0.100$	$F(1, 39) = 7.381, p = 0.010$*	$F(4, 39) = 0.150, p = 0.962$
Mandarin F1	50	$F(4, 40) = 0.550, p = 0.700$	$F(1, 40) = 3.985, p = 0.053$	$F(4, 40) = 0.534, p = 0.711$
Mandarin F2	49†	$F(4, 39) = 3.752, p = 0.011$*	$F(1, 39) = 0.121, p = 0.730$	$F(4, 39) = 0.812, p = 0.525$
Mandarin F3	45†	$F(4, 35) = 1.097, p = 0.373$	$F(1, 35) = 0.030, p = 0.863$	$F(4, 35) = 1.817, p = 0.148$
Mandarin F4	50	$F(4, 40) = 0.555, p = 0.696$	$F(1, 40) = 2.795, p = 0.102$	$F(4, 40) = 0.841, p = 0.507$
Mandarin F5	49†	$F(4, 39) = 0.465, p = 0.761$	$F(1, 39) = 0.0108, p = 0.918$	$F(4, 39) = 0.183, p = 0.946$
/a/				
Mandarin M1	55†	$F(6, 41) = 2.331, p = 0.050$	$F(1, 41) = 0.969, p = 0.331$	$F(6, 41) = 0.891, p = 0.511$
Mandarin M2	65†	$F(6, 51) = 2.578, p = 0.029$*	$F(1, 51) = 20.63, p < 0.001$**	$F(6, 51) = 1.593, p = 0.168$
Mandarin M3	68†	$F(6, 54) = 0.909, p = 0.496$	$F(1, 54) = 0.025, p = 0.876$	$F(6, 54) = 0.751, p = 0.611$
Mandarin M4	69†	$F(6, 55) = 0.520, p = 0.791$	$F(1, 55) = 6.686, p = 0.012$*	$F(6, 55) = 0.596, p = 0.732$
Mandarin M5	51†	$F(1, 43) = 1.383, p = 0.243$	$F(1, 43) = 4.078, p = 0.050$	--
Mandarin F1	69†	$F(6, 55) = 2.873, p = 0.017$*	$F(1, 55) = 0.319, p = 0.574$	$F(6, 55) = 1.422, p = 0.223$
Mandarin F2	70	$F(6, 56) = 1.806, p = 0.114$	$F(1, 56) = 0.003, p = 0.956$	$F(6, 56) = 1.720, p = 0.133$
Mandarin F3	70	$F(6, 56) = 0.671, p = 0.673$	$F(1, 56) = 0.000, p = 1.000$	$F(6, 56) = 0.791, p = 0.581$
Mandarin F4	70	$F(6, 56) = 1.021, p = 0.421$	$F(1, 56) = 0.508, p = 0.479$	$F(6, 56) = 0.868, p = 0.524$
Mandarin F5	69†	$F(6, 55) = 0.314, p = 0.927$	$F(1, 55) = 9.854, p = 0.003$**	$F(6, 55) = 0.731, p = 0.627$
/u/				
Mandarin M1	46†	$F(4, 36) = 7.402, p < 0.001$**	$F(1, 36) = 0.388, p = 0.537$	$F(4, 36) = 1.350, p = 0.271$
Mandarin M2	50	$F(4, 40) = 1.042, p = 0.398$	$F(1, 40) = 0.325, p = 0.572$	$F(4, 40) = 0.325, p = 0.859$
Mandarin M3	49†	$F(4, 39) = 2.320, p = 0.074$	$F(1, 39) = 4.554, p = 0.039$*	$F(4, 39) = 1.466, p = 0.231$
Mandarin M4	50	$F(4, 40) = 1.578, p = 0.199$	$F(1, 40) = 5.654, p = 0.022$*	$F(4, 40) = 1.935, p = 0.123$
Mandarin M5	50	$F(4, 40) = 0.487, p = 0.745$	$F(1, 40) = 8.862, p = 0.005$**	$F(4, 40) = 2.293, p = 0.076$
Mandarin F1	50	$F(4, 40) = 0.088, p = 0.986$	$F(1, 40) = 4.658, p = 0.037$*	$F(4, 40) = 0.852, p = 0.501$
Mandarin F2	50	$F(4, 40) = 1.918, p = 0.126$	$F(1, 40) = 0.131, p = 0.720$	$F(4, 40) = 1.113, p = 0.364$
Mandarin F3	50	$F(4, 40) = 3.224, p = 0.022$*	$F(1, 40) = 26.70, p < 0.001$**	$F(4, 40) = 0.757, p = 0.560$
Mandarin F4	50	$F(4, 40) = 0.861, p = 0.496$	$F(1, 40) = 2.258, p = 0.141$	$F(4, 40) = 1.552, p = 0.206$
Mandarin F5	49†	$F(4, 39) = 0.523, p = 0.719$	$F(1, 39) = 0.452, p = 0.505$	$F(4, 39) = 0.925, p = 0.459$

*Significant at 0.05 level
**Significant at 0.005 level
†Missing data

Appendix 25

Two-way (Tone by Task) ANOVA Results for Individual Mandarin Speakers – SQ90

Subject	N	Tone Effect	Task Effect	Tone x Task Interaction Effect
/i/				
Mandarin M1	10†	--	--	--
Mandarin M2	21†	F(3, 16) = 1.345, p = 0.295	F(1, 16) = 3.159, p = 0.095	--
Mandarin M3	35†	F(3, 27) = 8.190, p < 0.001**	F(1, 27) = 6.366, p = 0.018*	F(3, 27) = 1.138, p = 0.351
Mandarin M4	40	F(3, 32) = 4.870, p = 0.007**	F(1, 32) = 1.865, p = 0.182	F(3, 32) = 1.659, p = 0.195
Mandarin M5	28†	F(3, 20) = 1.378, p = 0.279	F(1, 20) = 0.047, p = 0.831	F(3, 20) = 2.152, p = 0.126
Mandarin F1	40	F(3, 32) = 9.925, p < 0.001**	F(1, 32) = 2E-12, p = 1.000	F(3, 32) = 0.512, p = 0.677
Mandarin F2	39†	F(3, 31) = 13.70, p < 0.001**	F(1, 31) = 0.003, p = 0.958	F(3, 31) = 0.537, p = 0.660
Mandarin F3	33†	F(3, 25) = 1.117, p = 0.361	F(1, 25) = 0.565, p = 0.459	F(3, 25) = 1.325, p = 0.288
Mandarin F4	40	F(3, 32) = 11.89, p < 0.001**	F(1, 32) = 8.220, p = 0.007**	F(3, 32) = 0.426, p = 0.735
Mandarin F5	36†	F(3, 28) = 3.329, p = 0.034*	F(1, 28) = 10.58, p = 0.003**	F(3, 28) = 1.622, p = 0.207
/a/				
Mandarin M1	13†	F(3, 8) = 4.1690, p = 0.047*	F(1, 8) = 0.0220, p = 0.886	--
Mandarin M2	24†	F(3, 16) = 1.053, p = 0.396	F(1, 16) = 0.167, p = 0.688	F(3, 16) = 3.181, p = 0.053
Mandarin M3	39†	F(3, 31) = 6.994, p < 0.001**	F(1, 31) = 0.890, p = 0.353	F(3, 31) = 3.849, p = 0.019
Mandarin M4	39†	F(3, 31) = 0.743, p = 0.534	F(1, 31) = 1.298, p = 0.263	F(3, 31) = 0.287, p = 0.834
Mandarin M5	15†	F(3, 10) = 0.012, p = 0.998	F(1, 10) = 0.371, p = 0.556	--
Mandarin F1	40	F(3, 32) = 2.810, p = 0.055	F(1, 32) = 0.597, p = 0.445	F(3, 32) = 0.754, p = 0.528
Mandarin F2	38†	F(3, 30) = 3.526, p = 0.027*	F(1, 30) = 3.050, p = 0.091	F(3, 30) = 1.647, p = 0.199
Mandarin F3	38†	F(3, 30) = 2.358, p = 0.091	F(1, 30) = 1.868, p = 0.182	F(3, 30) = 2.299, p = 0.098
Mandarin F4	40	F(3, 32) = 6.561, p = 0.001**	F(1, 32) = 5.969, p = 0.020*	F(3, 32) = 0.143, p = 0.933
Mandarin F5	38†	F(3, 30) = 16.38, p < 0.001**	F(1, 30) = 0.346, p = 0.561	F(3, 30) = 8.470, p < 0.001**
/u/				
Mandarin M1	22†	F(3, 17) = 4.718, p = 0.014*	F(1, 17) = 0.035, p = 0.854	--
Mandarin M2	32†	F(3, 27) = 6.871, p = 0.001**	F(1, 27) = 0.110, p = 0.743	--
Mandarin M3	26†	F(3, 21) = 0.428, p = 0.735	F(1, 21) = 0.287, p = 0.598	--
Mandarin M4	40	F(3, 32) = 2.635, p = 0.067	F(1, 32) = 1.796, p = 0.190	F(3, 32) = 0.725, p = 0.545
Mandarin M5	23†	F(3, 18) = 0.750, p = 0.536	F(1, 18) = 0.338, p = 0.568	--
Mandarin F1	40	F(3, 32) = 19.23, p < 0.001**	F(1, 32) = 2.953, p = 0.095	F(3, 32) = 1.107, p = 0.361
Mandarin F2	36†	F(3, 28) = 0.631, p = 0.601	F(1, 28) = 0.393, p = 0.536	F(3, 28) = 2.166, p = 0.114
Mandarin F3	40	F(3, 32) = 13.39, p < 0.001**	F(1, 32) = 4.164, p = 0.050	F(3, 32) = 0.623, p = 0.605
Mandarin F4	39†	F(3, 31) = 5.512, p = 0.004**	F(1, 31) = 4.442, p = 0.043*	F(3, 31) = 2.264, p = 0.101
Mandarin F5	38†	F(3, 30) = 13.51, p < 0.001**	F(1, 30) = 4.760, p = 0.037*	F(3, 30) = 13.71, p < 0.001**

*Significant at 0.05 level
**Significant at 0.005 level
†Missing data

Appendix 26

Two-way (Consonant by Task) ANOVA Results for Individual English Speakers – OQ90

Subject	N	Consonant Effect	Task Effect	Consonant x Task Interaction Effect
/i/				
English M1	31†	F(3, 23) = 2.095, p = 0.129	F(1, 23) = 0.0465, p = 0.831	F(3, 23) = 1.621, p = 0.212
English M2	16†	F(3, 11) = 0.936, p = 0.456	F(1, 11) = 2.4060, p = 0.149	--
English M3	37†	F(3, 29) = 4.536, p = 0.010*	F(1, 29) = 40.051, p < 0.001**	F(3, 29) = 0.394, p = 0.758
English M4	40	F(3, 32) = 2.927, p = 0.049*	F(1, 32) = 0.0914, p = 0.764	F(3, 32) = 2.521, p = 0.075
English M5	31†	F(3, 23) = 3.049, p = 0.049*	F(1, 23) = 15.560, p < 0.001**	F(3, 23) = 3.189, p = 0.043*
English F1	12†	F(3, 7) = 0.6810, p = 0.591	F(1, 7) = 4.13300, p = 0.082	--
English F2	37†	F(3, 29) = 0.960, p = 0.425	F(1, 29) = 0.4940, p = 0.488	F(3, 29) = 1.304, p = 0.292
English F3	40	F(3, 32) = 0.504, p = 0.682	F(1, 32) = 0.9230, p = 0.344	F(3, 32) = 0.791, p = 0.508
English F4	28†	F(3, 20) = 7.875, p = 0.001**	F(1, 20) = 0.0001, p = 0.993	F(3, 20) = 4.135, p = 0.020*
English F5	34†	F(3, 26) = 3.704, p = 0.024*	F(1, 26) = 0.7020, p = 0.410	F(3, 26) = 0.989, p = 0.413
/a/				
English M1	42†	F(5, 30) = 1.695, p = 0.166	F(1, 30) =0.1190, p = 0.732	F(5, 30) = 0.882, p = 0.505
English M2	30†	F(5, 23) = 1.377, p = 0.269	F(1, 23) =0.0179, p = 0.895	--
English M3	57†	F(5, 45) = 3.871, p = 0.005**	F(1, 45) =3.8260, p = 0.057	F(5, 45) = 1.275, p = 0.291
English M4	59†	F(5, 47) = 1.411, p = 0.238	F(1, 47) =0.0771, p = 0.783	F(5, 47) = 1.260, p = 0.297
English M5	49†	F(5, 37) = 0.969, p = 0.449	F(1, 37) =39.374, p < 0.001**	F(5, 37) = 0.683, p = 0.639
English F1	20†	--	--	--
English F2	59†	F(5, 47) = 0.592, p = 0.706	F(1, 47) = 0.4680, p = 0.497	F(5, 47) = 0.439, p = 0.819
English F3	59†	F(5, 47) = 2.607, p = 0.037*	F(1, 47) = 10.237, p = 0.002**	F(5, 47) = 1.754, p = 0.141
English F4	54†	F(5, 42) = 2.480, p = 0.047*	F(1, 42) = 0.0634, p = 0.802	F(5, 42) = 1.377, p = 0.252
English F5	46†	F(5, 34) = 1.040, p = 0.410	F(1, 34) = 3.2760, p = 0.079	F(5, 34) = 1.111, p = 0.373
/u/				
English M1	39†	F(3, 31) = 0.500, p = 0.685	F(1, 31) = 0.983, p = 0.329	F(3, 31) = 0.152, p = 0.928
English M2	19†	F(3, 14) = 2.267, p = 0.126	F(1, 14) = 4.878, p = 0.044*	--
English M3	36†	F(3, 28) = 4.333, p = 0.013*	F(1, 28) = 1.214, p = 0.280	F(3, 28) = 7.607, p < 0.001**
English M4	40	F(3, 32) = 2.201, p = 0.107	F(1, 32) = 10.090, p = 0.003**	F(3, 32) = 3.142, p = 0.039*
English M5	27†	F(3, 19) = 1.334, p = 0.293	F(1, 19) = 2.227, p = 0.152	F(3, 19) = 3.676, p = 0.031*
English F1	18†	F(3, 13) = 1.053, p = 0.402	F(1, 13) = 1.713, p = 0.213	--
English F2	23†	F(3, 15) = 1.285, p = 0.315	F(1, 15) = 8.344, p = 0.011*	F(3, 15) = 0.839, p = 0.493
English F3	39†	F(3, 31) = 0.369, p = 0.776	F(1, 31) = 21.92, p < 0.001**	F(3, 31) = 0.524, p = 0.669
English F4	28†	F(3, 20) = 0.345, p = 0.793	F(1, 20) = 2.906, p = 0.104	F(3, 20) = 1.003, p = 0.412
English F5	27†	F(3, 19) = 0.852, p = 0.483	F(1, 19) = 0.176, p = 0.679	F(3, 19) = 1.678, p = 0.206

*Significant at 0.05 level
**Significant at 0.005 level
†Missing data

Appendix 27

Two-way (Consonant by Task) ANOVA Results for Individual Mandarin Speakers – OQ90

Subject	N	Consonant Effect	Task Effect	Consonant x Task Interaction Effect
/i/				
Mandarin M1	28†	$F(4, 22) = 1.153, p = 0.358$	$F(1, 22) = 0.202, p = 0.657$	--
Mandarin M2	43†	$F(4, 33) = 0.271, p = 0.895$	$F(1, 33) = 0.036, p = 0.851$	$F(4, 33) = 1.219, p = 0.321$
Mandarin M3	49†	$F(4, 39) = 1.339, p = 0.273$	$F(1, 39) = 1.108, p = 0.299$	$F(4, 39) = 1.911, p = 0.128$
Mandarin M4	50	$F(4, 40) = 0.516, p = 0.724$	$F(1, 40) = 1.107, p = 0.299$	$F(4, 40) = 2.865, p = 0.035$*
Mandarin M5	49†	$F(4, 39) = 2.609, p = 0.050$	$F(1, 39) = 12.73, p < 0.001$**	$F(4, 39) = 0.091, p = 0.985$
Mandarin F1	50	$F(4, 40) = 0.515, p = 0.725$	$F(1, 40) = 14.80, p < 0.001$**	$F(4, 40) = 0.638, p = 0.638$
Mandarin F2	49†	$F(4, 39) = 3.322, p = 0.020$*	$F(1, 39) = 0.219, p = 0.643$	$F(4, 39) = 1.198, p = 0.327$
Mandarin F3	45†	$F(4, 35) = 1.147, p = 0.351$	$F(1, 35) = 0.135, p = 0.715$	$F(4, 35) = 1.473, p = 0.231$
Mandarin F4	50	$F(4, 40) = 0.569, p = 0.687$	$F(1, 40) = 3.042, p = 0.089$	$F(4, 40) = 0.898, p = 0.474$
Mandarin F5	49†	$F(4, 39) = 0.538, p = 0.709$	$F(1, 39) = 0.126, p = 0.724$	$F(4, 39) = 0.229, p = 0.920$
/a/				
Mandarin M1	55†	$F(6, 41) = 2.083, p = 0.076$	$F(1, 41) = 0.305, p = 0.584$	$F(6, 41) = 0.661, p = 0.682$
Mandarin M2	65†	$F(6, 51) = 2.451, p = 0.037$*	$F(1, 51) = 19.73, p < 0.001$**	$F(6, 51) = 1.697, p = 0.141$
Mandarin M3	68†	$F(6, 54) = 1.221, p = 0.310$	$F(1, 54) = 0.003, p = 0.960$	$F(6, 54) = 0.459, p = 0.835$
Mandarin M4	69†	$F(6, 55) = 0.649, p = 0.691$	$F(1, 55) = 4.579, p = 0.037$*	$F(6, 55) = 0.554, p = 0.765$
Mandarin M5	51†	$F(1, 43) = 0.927, p = 0.486$	$F(1, 43) = 6.918, p = 0.012$*	--
Mandarin F1	69†	$F(6, 55) = 2.735, p = 0.021$*	$F(1, 55) = 0.933, p = 0.338$	$F(6, 55) = 1.276, p = 0.283$
Mandarin F2	70	$F(6, 56) = 1.457, p = 0.210$	$F(1, 56) = 0.642, p = 0.426$	$F(6, 56) = 1.320, p = 0.263$
Mandarin F3	70	$F(6, 56) = 0.552, p = 0.766$	$F(1, 56) = 2.546, p = 0.116$	$F(6, 56) = 1.313, p = 0.267$
Mandarin F4	70	$F(6, 56) = 1.297, p = 0.274$	$F(1, 56) = 1.641, p = 0.205$	$F(6, 56) = 1.110, p = 0.368$
Mandarin F5	69†	$F(6, 55) = 0.483, p = 0.818$	$F(1, 55) = 5.667, p = 0.021$*	$F(6, 55) = 0.936, p = 0.477$
/u/				
Mandarin M1	46†	$F(4, 36) = 5.811, p = 0.001$**	$F(1, 36) = 0.077, p = 0.783$	$F(4, 36) = 1.543, p = 0.211$
Mandarin M2	50	$F(4, 40) = 1.040, p = 0.399$	$F(1, 40) = 0.494, p = 0.486$	$F(4, 40) = 0.311, p = 0.869$
Mandarin M3	49†	$F(4, 39) = 2.055, p = 0.105$	$F(1, 39) = 0.157, p = 0.694$	$F(4, 39) = 1.429, p = 0.243$
Mandarin M4	50	$F(4, 40) = 1.731, p = 0.162$	$F(1, 40) = 2.114, p = 0.154$	$F(4, 40) = 1.688, p = 0.172$
Mandarin M5	50	$F(4, 40) = 0.364, p = 0.833$	$F(1, 40) = 19.07, p < 0.001$**	$F(4, 40) = 2.446, p = 0.062$
Mandarin F1	50	$F(4, 40) = 0.058, p= 0.994$	$F(1, 40) = 6.139, p = 0.018$*	$F(4, 40) = 0.979, p = 0.430$
Mandarin F2	50	$F(4, 40) = 1.895, p = 0.130$	$F(1, 40) = 0.019, p = 0.891$	$F(4, 40) = 1.453, p = 0.235$
Mandarin F3	50	$F(4, 40) = 4.301, p = 0.005$**	$F(1, 40) = 13.63, p < 0.001$**	$F(4, 40) = 0.579, p = 0.679$
Mandarin F4	50	$F(4, 40) = 0.560, p = 0.693$	$F(1, 40) = 5.126, p = 0.029$*	$F(4, 40) = 1.316, p = 0.281$
Mandarin F5	49†	$F(4, 39) = 0.485, p = 0.746$	$F(1, 39) = 0.715, p = 0.403$	$F(4, 39) = 0.999, p = 0.420$

*Significant at 0.05 level
**Significant at 0.005 level
†Missing data

Appendix 28

Two-way (Tone by Task) ANOVA Results for Individual Mandarin Speakers – OQ90

Subject	N	Tone Effect	Task Effect	Tone x Task Interaction Effect
/i/				
Mandarin M1	10†	--	--	--
Mandarin M2	21†	$F(3, 16) = 3.057, p = 0.059$	$F(1, 16) = 4.831, p = 0.043$*	--
Mandarin M3	35†	$F(3, 27) = 5.232, p = 0.006$**	$F(1, 27) = 7.419, p = 0.011$*	$F(3, 27) = 0.701, p = 0.560$
Mandarin M4	40	$F(3, 32) = 5.677, p = 0.003$**	$F(1, 32) = 1.136, p = 0.295$	$F(3, 32) = 2.101, p = 0.120$
Mandarin M5	28†	$F(3, 20) = 2.135, p = 0.128$	$F(1, 20) = 0.399, p = 0.535$	$F(3, 20) = 2.020, p = 0.143$
Mandarin F1	40	$F(3, 32) = 12.10, p < 0.001$**	$F(1, 32) = 0.552, p = 0.463$	$F(3, 32) = 1.119, p = 0.356$
Mandarin F2	39†	$F(3, 31) = 9.819, p < 0.001$**	$F(1, 31) = 0.146, p = 0.705$	$F(3, 31) = 1.074, p = 0.374$
Mandarin F3	33†	$F(3, 25) = 1.419, p = 0.261$	$F(1, 25) = 0.217, p = 0.646$	$F(3, 25) = 1.403, p = 0.265$
Mandarin F4	40	$F(3, 32) = 11.41, p < 0.001$**	$F(1, 32) = 11.745, p = 0.002$**	$F(3, 32) = 0.569, p = 0.639$
Mandarin F5	36†	$F(3, 28) = 1.974, p = 0.141$	$F(1, 28) = 11.577, p = 0.002$**	$F(3, 28) = 2.347, p = 0.094$
/a/				
Mandarin M1	13†	$F(3, 8) = 4.4730, p = 0.040$*	$F(1, 8) = 2.9650, p = 0.123$	--
Mandarin M2	24†	$F(3, 16) = 0.982, p = 0.426$	$F(1, 16) = 0.001, p = 0.981$	$F(3, 16) = 1.525, p = 0.246$
Mandarin M3	39†	$F(3, 31) = 4.343, p = 0.011$*	$F(1, 31) = 0.933, p = 0.342$	$F(3, 31) = 3.210, p = 0.036$*
Mandarin M4	39†	$F(3, 31) = 0.538, p = 0.665$	$F(1, 31) = 1.778, p = 0.192$	$F(3, 31) = 0.509, p = 0.679$
Mandarin M5	15†	$F(3, 10) = 0.105, p = 0.955$	$F(1, 10) = 0.434, p = 0.525$	--
Mandarin F1	40	$F(3, 32) = 2.852, p = 0.053$	$F(1, 32) = 0.392, p = 0.536$	$F(3, 32) = 0.847, p = 0.478$
Mandarin F2	38†	$F(3, 30) = 2.108, p = 0.120$	$F(1, 30) = 4.886, p = 0.035$*	$F(3, 30) = 2.307, p = 0.097$
Mandarin F3	38†	$F(3, 30) = 4.712, p = 0.008$**	$F(1, 30) = 0.144, p = 0.707$	$F(3, 30) = 3.442, p = 0.029$*
Mandarin F4	40	$F(3, 32) = 5.945, p = 0.002$**	$F(1, 32) = 7.860, p = 0.009$**	$F(3, 32) = 0.262, p = 0.852$
Mandarin F5	38†	$F(3, 30) = 20.25, p < 0.001$**	$F(1, 30) = 4.494, p = 0.042$*	$F(3, 30) = 13.718, p < 0.001$**
/u/				
Mandarin M1	22†	$F(3, 17) = 4.413, p = 0.018$*	$F(1, 17) = 0.582, p = 0.456$	--
Mandarin M2	32†	$F(3, 27) = 4.854, p = 0.008$**	$F(1, 27) = 0.614, p = 0.440$	--
Mandarin M3	26†	$F(3, 21) = 0.119, p = 0.948$	$F(1, 21) = 0.284, p = 0.600$	--
Mandarin M4	40	$F(3, 32) = 3.514, p = 0.026$*	$F(1, 32) = 1.033, p = 0.317$	$F(3, 32) = 0.515, p = 0.675$
Mandarin M5	23†	$F(3, 18) = 1.584, p = 0.228$	$F(1, 18) = 0.833, p = 0.374$	--
Mandarin F1	40	$F(3, 32) = 50.19, p < 0.001$**	$F(1, 32) = 6.174, p = 0.018$*	$F(3, 32) = 1.179, p = 0.333$
Mandarin F2	36†	$F(3, 28) = 0.825, p = 0.491$	$F(1, 28) = 2.748, p = 0.109$	$F(3, 28) = 2.309, p = 0.098$
Mandarin F3	40	$F(3, 32) = 12.55, p < 0.001$**	$F(1, 32) = 2.282, p = 0.141$	$F(3, 32) = 0.889, p = 0.457$
Mandarin F4	39†	$F(3, 31) = 5.211, p = 0.005$**	$F(1, 31) = 6.401, p = 0.017$*	$F(3, 31) = 1.313, p = 0.288$
Mandarin F5	38†	$F(3, 30) = 16.949, p < 0.001$**	$F(1, 30) = 5.889, p = 0.021$*	$F(3, 30) = 17.395, p < 0.001$**

*Significant at 0.05 level
**Significant at 0.005 level
†Missing data

Appendix 29

Two-way (Consonant by Task) ANOVA Results for Individual English Speakers – C-Length

Subject	N	Consonant Effect	Task Effect	Consonant x Task Interaction Effect
/i/				
English M1	40	$F(3, 32) = 336.730, p < 0.001$**	$F(1, 32) = 4.356, p = 0.045$*	$F(3, 32) = 1.368, p = 0.270$
English M2	40	$F(3, 32) = 195.452, p < 0.001$**	$F(1, 32) = 1.389, p = 0.247$	$F(3, 32) = 1.915, p = 0.147$
English M3	40	$F(3, 32) = 101.136, p < 0.001$**	$F(1, 32) = 1.679, p = 0.204$	$F(3, 32) = 0.685, p = 0.568$
English M4	40	$F(3, 32) = 288.148, p < 0.001$**	$F(1, 32) = 2.809, p = 0.104$	$F(3, 32) = 5.388, p = 0.004$**
English M5	40	$F(3, 32) = 117.509, p < 0.001$**	$F(1, 32) = 2.521, p = 0.122$	$F(3, 32) = 0.329, p = 0.805$
English F1	40	$F(3, 32) = 117.188, p < 0.001$**	$F(1, 32) = 5.284, p = 0.028$*	$F(3, 32) = 3.119, p = 0.040$*
English F2	40	$F(3, 32) = 99.797, p < 0.001$**	$F(1, 32) = 14.370, p < 0.001$**	$F(3, 32) = 11.899, p < 0.001$**
English F3	40	$F(3, 32) = 177.923, p < 0.001$**	$F(1, 32) = 63.428, p < 0.001$**	$F(3, 32) = 18.838, p < 0.001$**
English F4	40	$F(3, 32) = 348.902, p < 0.001$**	$F(1, 32) = 9.259, p = 0.005$**	$F(3, 32) = 9.354, p < 0.001$**
English F5	40	$F(3, 32) = 138.144, p < 0.001$**	$F(1, 32) = 0.388, p = 0.538$	$F(3, 32) = 0.270, p = 0.847$
/a/				
English M1	60	$F(5, 48) = 66.151, p < 0.001$**	$F(1, 48) = 0.00445, p = 0.947$	$F(5, 48) = 0.322, p = 0.897$
English M2	59†	$F(5, 47) = 93.509, p < 0.001$**	$F(1, 47) = 7.238, p = 0.010$*	$F(5, 47) = 2.396, p = 0.051$
English M3	60	$F(5, 48) = 83.875, p < 0.001$**	$F(1, 48) = 6.458, p = 0.014$*	$F(5, 48) = 2.374, p = 0.053$
English M4	60	$F(5, 48) = 364.898, p < 0.001$**	$F(1, 48) = 0.439, p = 0.511$	$F(5, 48) = 0.885, p = 0.498$
English M5	60	$F(5, 48) = 68.293, p < 0.001$**	$F(1, 48) = 1.167, p = 0.285$	$F(5, 48) = 1.219, p = 0.315$
English F1	60	$F(5, 48) = 92.315, p < 0.001$**	$F(1, 48) = 5.131, p = 0.028$*	$F(5, 48) = 6.002, p < 0.001$**
English F2	60	$F(5, 48) = 122.200, p < 0.001$**	$F(1, 48) = 6.296, p = 0.016$*	$F(5, 48) = 0.796, p = 0.558$
English F3	59†	$F(5, 47) = 100.461, p < 0.001$**	$F(1, 47) = 39.393, p < 0.001$**	$F(5, 47) = 5.298, p < 0.001$**
English F4	60	$F(5, 48) = 246.980, p < 0.001$**	$F(1, 48) = 10.966, p = 0.002$**	$F(5, 48) = 5.576, p < 0.001$**
English F5	60	$F(5, 48) = 116.469, p < 0.001$**	$F(1, 48) = 6.181, p = 0.016$*	$F(5, 48) = 0.431, p = 0.825$
/u/				
English M1	40	$F(3, 32) = 130.126, p < 0.001$**	$F(1, 32) = 1.894, p = 0.178$	$F(3, 32) = 1.885, p = 0.152$
English M2	40	$F(3, 32) = 19.903, p < 0.001$**	$F(1, 32) = 0.426, p = 0.519$	$F(3, 32) = 0.717, p = 0.549$
English M3	39†	$F(3, 32) = 87.395, p < 0.001$**	$F(1, 32) = 0.0349, p = 0.853$	$F(3, 32) = 1.632, p = 0.202$
English M4	40	$F(3, 32) = 266.945, p < 0.001$**	$F(1, 32) = 1.443, p = 0.239$	$F(3, 32) = 0.121, p = 0.947$
English M5	38†	$F(3, 30) = 68.626, p < 0.001$**	$F(1, 30) = 0.108, p = 0.745$	$F(3, 30) = 0.185, p = 0.906$
English F1	40	$F(3, 32) = 139.301, p < 0.001$**	$F(1, 32) = 1.508, p = 0.228$	$F(3, 32) = 3.797, p = 0.020$*
English F2	40	$F(3, 32) = 136.928, p < 0.001$**	$F(1, 32) = 13.567, p < 0.001$**	$F(3, 32) = 4.684, p = 0.008$**
English F3	40	$F(3, 32) = 87.345, p < 0.001$**	$F(1, 32) = 29.715, p < 0.001$**	$F(3, 32) = 9.043, p < 0.001$**
English F4	40	$F(3, 32) = 3.448, p = 0.028$*	$F(1, 32) = 0.427, p = 0.518$	$F(3, 32) = 1.448, p = 0.247$
English F5	38†	$F(3, 30) = 61.737, p < 0.001$**	$F(1, 30) = 0.0159, p = 0.901$	$F(3, 30) = 0.768, p = 0.521$

*Significant at 0.05 level
**Significant at 0.005 level
†Missing data

Appendix 30

Two-way (Consonant by Task) ANOVA Results for Individual Mandarin Speakers – C-Length

Subject	N	Consonant Effect	Task Effect	Consonant x Task Interaction Effect
/i/				
Mandarin M1	50	$F(4, 40) = 114.502, p < 0.001$**	$F(1, 40) = 4.021, p = 0.052$	$F(4, 40) = 2.011, p = 0.111$
Mandarin M2	49†	$F(4, 39) = 108.199, p < 0.001$**	$F(1, 39) = 0.0491, p = 0.826$	$F(4, 39) = 4.113, p = 0.007$**
Mandarin M3	50	$F(4, 40) = 40.872, p < 0.001$**	$F(1, 40) = 0.285, p = 0.596$	$F(4, 40) = 1.136, p = 0.353$
Mandarin M4	50	$F(4, 40) = 45.731, p < 0.001$**	$F(1, 40) = 0.0137, p = 0.907$	$F(4, 40) = 0.181, p = 0.947$
Mandarin M5	50	$F(4, 40) = 14.338, p < 0.001$**	$F(1, 40) = 0.434, p = 0.514$	$F(4, 40) = 0.478, p = 0.751$
Mandarin F1	50	$F(4, 40) = 81.012, p < 0.001$**	$F(1, 40) = 2.617, p = 0.114$	$F(4, 40) = 2.705, p = 0.044$*
Mandarin F2	49†	$F(4, 39) = 146.551, p < 0.001$**	$F(1, 39) = 4.013, p = 0.052$	$F(4, 39) = 2.647, p = 0.048$*
Mandarin F3	49†	$F(4, 39) = 119.704, p < 0.001$**	$F(1, 39) = 5.403, p = 0.025$*	$F(4, 39) = 5.266, p = 0.002$**
Mandarin F4	50	$F(4, 40) = 66.615, p < 0.001$**	$F(1, 40) = 0.109, p = 0.743$	$F(4, 40) = 3.975, p = 0.008$**
Mandarin F5	50	$F(4, 40) = 471.663, p < 0.001$**	$F(1, 40) = 96.702, p < 0.001$**	$F(4, 40) = 60.407, p < 0.001$**
/a/				
Mandarin M1	70	$F(6, 56) = 187.811, p < 0.001$**	$F(1, 56) = 0.0987, p = 0.755$	$F(6, 56) = 3.062, p = 0.012$*
Mandarin M2	68†	$F(6, 54) = 126.659, p < 0.001$**	$F(1, 54) = 18.561, p < 0.001$**	$F(6, 54) = 5.600, p < 0.001$**
Mandarin M3	69†	$F(6, 55) = 115.753, p < 0.001$**	$F(1, 55) = 5.511, p = 0.023$*	$F(6, 55) = 2.119, p = 0.066$
Mandarin M4	69†	$F(6, 55) = 50.750, p < 0.001$**	$F(1, 55) = 0.0000638, p = 0.994$	$F(6, 55) = 0.408, p = 0.870$
Mandarin M5	70	$F(6, 56) = 68.473, p < 0.001$**	$F(1, 56) = 3.271, p = 0.076$	$F(6, 56) = 0.197, p = 0.976$
Mandarin F1	69†	$F(6, 55) = 31.559, p < 0.001$**	$F(1, 55) = 2.356, p = 0.131$	$F(6, 55) = 2.531, p = 0.031$*
Mandarin F2	70	$F(6, 56) = 134.672, p < 0.001$**	$F(1, 56) = 0.781, p = 0.381$	$F(6, 56) = 1.189, p = 0.326$
Mandarin F3	70	$F(6, 56) = 128.358, p < 0.001$**	$F(1, 56) = 12.338, p < 0.001$**	$F(6, 56) = 3.440, p = 0.006$**
Mandarin F4	70	$F(6, 56) = 128.017, p < 0.001$**	$F(1, 56) = 2.410, p = 0.126$	$F(6, 56) = 0.724, p = 0.632$
Mandarin F5	70	$F(6, 56) = 246.883, p < 0.001$**	$F(1, 56) = 137.423, p < 0.001$**	$F(6, 56) = 31.099, p < 0.001$**
/u/				
Mandarin M1	50	$F(4, 40) = 152.919, p < 0.001$**	$F(1, 40) = 7.335, p = 0.010$*	$F(4, 40) = 3.688, p = 0.012$*
Mandarin M2	50	$F(4, 40) = 70.179, p < 0.001$**	$F(1, 40) = 0.730, p = 0.398$	$F(4, 40) = 1.259, p = 0.302$
Mandarin M3	50	$F(4, 40) = 49.863, p < 0.001$**	$F(1, 40) = 0.791, p = 0.379$	$F(4, 40) = 3.047, p = 0.028$*
Mandarin M4	50	$F(4, 40) = 74.000, p < 0.001$**	$F(1, 40) = 9.250, p = 0.004$**	$F(4, 40) = 0.390, p = 0.814$
Mandarin M5	50	$F(4, 40) = 38.023, p < 0.001$**	$F(1, 40) = 0.0761, p = 0.784$	$F(4, 40) = 2.916, p = 0.033$*
Mandarin F1	50	$F(4, 40) = 110.541, p < 0.001$**	$F(1, 40) = 18.472, p < 0.001$**	$F(4, 40) = 4.253, p = 0.006$**
Mandarin F2	50	$F(4, 40) = 82.501, p < 0.001$**	$F(1, 40) = 0.474, p = 0.495$	$F(4, 40) = 1.391, p = 0.254$
Mandarin F3	50	$F(4, 40) = 83.933, p < 0.001$**	$F(1, 40) = 0.530, p = 0.471$	$F(4, 40) = 0.545, p = 0.704$
Mandarin F4	50	$F(4, 40) = 147.162, p < 0.001$**	$F(1, 40) = 0.789, p = 0.380$	$F(4, 40) = 1.047, p = 0.395$
Mandarin F5	50	$F(4, 40) = 59.677, p < 0.001$**	$F(1, 40) = 15.868, p < 0.001$**	$F(4, 40) = 5.215, p = 0.002$**

*Significant at 0.05 level
**Significant at 0.005 level
†Missing data

Appendix 31

Two-way (Tone by Task) ANOVA Results for Individual Mandarin Speakers – C-Length

Subject	N	Tone Effect	Task Effect	Tone x Task Interaction Effect
/i/				
Mandarin M1	40	F(3, 32) = 0.232, p = 0.874	F(1, 32) = 4.271, p = 0.047*	F(3, 32) = 0.453, p = 0.717
Mandarin M2	40	F(3, 32) = 0.690, p = 0.565	F(1, 32) = 19.533, p < 0.001**	F(3, 32) = 0.160, p = 0.922
Mandarin M3	40	F(3, 32) = 0.467, p = 0.707	F(1, 32) = 0.598, p = 0.445	F(3, 32) = 0.0923, p = 0.964
Mandarin M4	40	F(3, 32) = 6.386, p = 0.002**	F(1, 32) = 0.408, p = 0.527	F(3, 32) = 0.667, p = 0.579
Mandarin M5	40	F(3, 32) = 2.743, p = 0.059	F(1, 32) = 5.394, p = 0.027*	F(3, 32) = 1.714, p = 0.184
Mandarin F1	40	F(3, 32) = 0.298, p = 0.826	F(1, 32) = 5.019, p = 0.032*	F(3, 32) = 0.597, p = 0.622
Mandarin F2	40	F(3, 32) = 1.753, p = 0.176	F(1, 32) = 13.526, p < 0.001**	F(3, 32) = 3.213, p = 0.036*
Mandarin F3	40	F(3, 32) = 0.159, p = 0.923	F(1, 32) = 4.811, p = 0.036*	F(3, 32) = 0.396, p = 0.757
Mandarin F4	40	F(3, 32) = 3.194, p = 0.037*	F(1, 32) = 16.227, p < 0.001**	F(3, 32) = 0.519, p = 0.672
Mandarin F5	40	F(3, 32) = 2.019, p = 0.131	F(1, 32) = 1.054, p = 0.312	F(3, 32) = 0.559, p = 0.646
/a/				
Mandarin M1	40	F(3, 32) = 0.376, p = 0.771	F(1, 32) = 7.898, p = 0.008**	F(3, 32) = 0.311, p = 0.817
Mandarin M2	39†	F(3, 31) = 0.350, p = 0.789	F(1, 31) = 0.748, p = 0.394	F(3, 31) = 0.388, p = 0.763
Mandarin M3	40	F(3, 32) = 0.268, p = 0.848	F(1, 32) = 0.00495, p = 0.944	F(3, 32) = 1.680, p = 0.191
Mandarin M4	39†	F(3, 31) = 0.905, p = 0.450	F(1, 31) = 0.330, p = 0.570	F(3, 31) = 0.191, p = 0.901
Mandarin M5	40	F(3, 32) = 0.637, p = 0.597	F(1, 32) = 0.244, p = 0.625	F(3, 32) = 0.791, p = 0.508
Mandarin F1	40	F(3, 32) = 1.009, p = 0.401	F(1, 32) = 0.0175, p = 0.896	F(3, 32) = 0.0766, p = 0.972
Mandarin F2	40	F(3, 32) = 0.0691, p = 0.976	F(1, 32) = 0.975, p = 0.331	F(3, 32) = 1.770, p = 0.173
Mandarin F3	40	F(3, 32) = 1.026, p = 0.394	F(1, 32) = 0.274, p = 0.604	F(3, 32) = 1.144, p = 0.346
Mandarin F4	40	F(3, 32) = 0.824, p = 0.491	F(1, 32) = 1.115, p = 0.299	F(3, 32) = 0.548, p = 0.653
Mandarin F5	40	F(3, 32) = 3.857, p = 0.018*	F(1, 32) = 1.491, p = 0.231	F(3, 32) = 0.507, p = 0.680
/u/				
Mandarin M1	40	F(3, 32) = 0.580, p = 0.632	F(1, 32) = 13.525, p < 0.001**	F(3, 32) = 0.730, p = 0.542
Mandarin M2	39†	F(3, 31) = 2.325, p = 0.094	F(1, 31) = 0.0388, p = 0.845	F(3, 31) = 0.766, p = 0.522
Mandarin M3	40	F(3, 32) = 1.620, p = 0.204	F(1, 32) = 0.422, p = 0.521	F(3, 32) = 1.395, p = 0.262
Mandarin M4	40	F(3, 32) = 0.899, p = 0.453	F(1, 32) = 0.587, p = 0.449	F(3, 32) = 0.695, p = 0.562
Mandarin M5	40	F(3, 32) = 3.042, p = 0.043*	F(1, 32) = 2.611, p = 0.116	F(3, 32) = 2.909, p = 0.050
Mandarin F1	40	F(3, 32) = 0.437, p = 0.728	F(1, 32) = 14.179, p < 0.001**	F(3, 32) = 0.886, p = 0.459
Mandarin F2	40	F(3, 32) = 2.878, p = 0.051	F(1, 32) = 1.172, p = 0.287	F(3, 32) = 0.755, p = 0.529
Mandarin F3	40	F(3, 32) = 2.195, p = 0.108	F(1, 32) = 3.927, p = 0.056	F(3, 32) = 0.467, p = 0.707
Mandarin F4	40	F(3, 32) = 2.477, p = 0.079	F(1, 32) = 1.650, p = 0.208	F(3, 32) = 0.780, p = 0.514
Mandarin F5	39†	F(3, 31) = 2.662, p = 0.065	F(1, 31) = 5.178, p = 0.030*	F(3, 31) = 0.392, p = 0.759

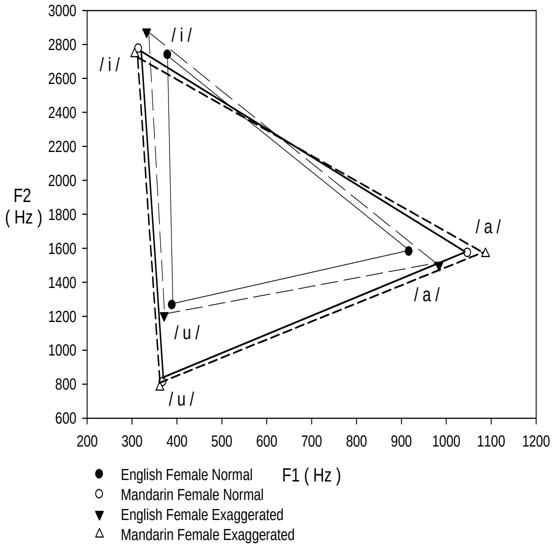
*Significant at 0.05 level
**Significant at 0.005 level
†Missing data

Appendix 32

A Comparison of Vowel Space in Males and Females from

English and Mandarin Groups

Females



Males